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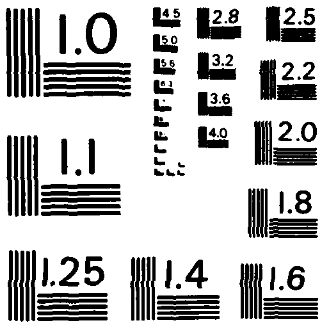

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TECHNICAL REPORT
SIMULATION EXPERIMENT

AN INVESTIGATION OF THE RELATIVE SAFETY OF ALTERNATIVE NAVIGATIONAL SYSTEM DESIGNS FOR THE NEW SUNSHINE SKYWAY BRIDGE: A CAORF SIMULATION

U.S. DEPARTMENT OF TRANSPORTATION

MARITIME ADMINISTRATION
OFFICE OF SHIPBUILDING, OPERATIONS, AND RESEARCH

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16. Abstracts

This report describes an investigation performed for the Florida State Department of Transportation (FDOT) to determine the relative safety afforded the new Sunshine Skyway Bridge by three alternative navigational system designs. A "navigational system design" was a specific configuration of channels, aids to navigation, and shipboard navigation aids in the vicinity of the bridge. The first design included a relocation and redesign of the new bridge when compared with the existing bridge. The second design included the availability of a precision electronic aid to aid pilots in determining their position. The third design included a redesign of the channel approach to the bridge which displaced a course change that was less than one nautical mile to almost three nautical miles from the bridge. A fourth design was also included in the study to serve as a baseline condition against which to compare the three alternatives. This design was modelled to include the existing Sunshine Skyway Bridge and the channel and aids to navigation configuration that existed in May 1980 when the SUMMIT VENTURE struck the bridge causing extensive damage to the bridge and the loss of 35 lives. Nine scenarios were developed to compare bridge safety of the four designs during the transit of a 160,000 DWT tanker. Safety was principally defined in terms of measures of vessels proximity to bridge structures. The transits were generally made during adverse conditions consisting of heavy fog or thunderstorms. A limited number of transits were made under favorable environmental conditions to aid in the establishment of baseline levels of performance.The transits were made by seven Tampa Bay pilots. The results indicated that vessel transit

(Continued on following page)

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Channel Design	Navigation Hazards
Computer Aided Operations Research Facility	Port Design
Computer Generated Imagery	Port Safety
Computer Simulation	Precision Navigation Aids
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16. Abstracts (cont'd)

under thunderstorm conditions were less safe than transits under fog conditions. All three of the navigational system designs were found to be safer than the design that existed in 1980. Of the three alternatives, the design which included the precision electronic navigation aid was found to provide greater bridge safety than the other two. The redesign of the channel approach was not found to provide additional safety beyond the relocation and redesign of the bridge alone. It was, therefore, recommended that the design alternative including the precision electronic aid be supported and the design including the channel redesign not be supported.

CAORF 26-8232-04

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EXECUTIVE SUMMARY

The Sunshine Skyway Bridge extends across the southern end of Tampa Bay connecting Manatee County and Pinellas County, Florida. It is a twin span structure 27,373 feet long and serves as part of Interstate 275. The bridge passes over the main ship channel which links the ports of Tampa Bay with the Gulf of Mexico and is, therefore, exposed to heavy vessel traffic. The bridge provides 800 feet of horizontal clearance and 149 feet of vertical clearance for vessels transiting under it. Currently, only the eastern span of the bridge is available; the western span was destroyed in 1980 as the result of the impact from a large vessel which strayed from the ship channel during an intense thunderstorm. In addition to extensive monetary losses, 35 lives were lost in the accident.

Rather than repair the existing damaged span, a replacement bridge will be built adjacent to the location of the existing structure. The Florida Department of Transportation (FDOT) has spearheaded a comprehensive risk management and engineering design effort to ensure that the replacement Sunshine Skyway Bridge is part of an overall bridge and waterway system that minimizes the likelihood of future vessel-bridge collisions.

This study was a part of that risk management effort. It utilized the U.S. Maritime Administration's Computer Aided Operations Research Facility (CAORF) which houses a real-time, full-mission shiphandling simulator to examine the relative safety of several "navigational system designs" incorporating the Sunshine Skyway Bridge. The framework in which this research was viewed can be considered a system design approach. The safety of a bridge is considered as part of an overall system. Important factors in the system are organized into several major categories including bridge characteristics, waterway characteristics, aids to navigation, vessel characteristics, operator characteristics, traffic conditions, and miscellaneous other factors. The approach taken here is that it is the interaction of these components as a single system rather than any one single factor in isolation which influences bridge safety. Hence, it is the design of the entire system that is of major importance. When vessel transit through a bridge is of primary concern the term "navigational system design" can be used to emphasize the focus on the system's design for vessel navigation. Therefore, as the term is being used here, "navigational system designs" refers to the specific configurations of bridges, channels, aids to navigation, and shipboard navigation aids under investigation. The study examined the operational safety of several such system designs under a variety of environmental conditions using real time man-in-the-loop simulation. The study, therefore, represented an effort to mitigate the risk of future vessel-bridge incidents.

Three risk mitigation strategies were examined. The first involved the decision to position the replacement bridge approximately 1,000 feet further away from the 18 degree turn from Mullet Key Channel into Cut A Channel which is currently about .7 nm from the existing bridge. In addition, the horizontal clearance between the main bridge piers will be increased and an elaborate pier protection system will be developed.

The second strategy to mitigate the risk of a vessel collision with the bridge was the displacement of the turn into Cut A Channel from .7 nm to 2.7 nm seaward of its present location. This would be accomplished by the extension of Cut A Channel approximately 2 nm to the west. The extended Cut A Channel would be joined with an extension of Egmont Channel thus eliminating Mullet Key Channel as a primary ship route. This alternative would, however, increase the turn from 18 to 35 degrees.

The third strategy investigated was the utilization by Tampa Bay pilots of a precision electronic navigation aid. The aid would be used by pilots aboard ship and would provide precise navigation information such as vessel's distance off the channel centerline.

Three navigational system designs were developed to incorporate the three risk mitigation strategies. A fourth system design was also developed in order to estimate the degree of relative safety afforded by the three alternative designs. The fourth design was a model of Tampa Bay as it existed in early 1980 prior to the aforementioned collision of a vessel with the Sunshine Skyway Bridge. The purpose of this fourth design was to provide a baseline level of performance (or yardstick) against which the alternative

designs were compared. A brief description of the four navigational system designs is provided below.

- Navigational System Design 1 – The original Sunshine Skyway Bridge in its original position, with the channel alignment and navigational aids as they existed in May of 1980 when the SUMMIT VENTURE incident occured.

- Navigational System Design 2 – The new Sunshine Skyway Bridge with the currently existing channel alignment and recently improved navigational aids.

- Navigational System Design 3 – The new Sunshine Skyway Bridge with the currently existing channel alignment and recently improved navigational aids. In addition, a precision electronic navigation aid was included in this system.

- Navigational System Design 4 – The new Sunshine Skyway Bridge with a new channel alignment consisting of the extension of Cut A Channel and a system of floating aids consistent with the markings of other channels and bends in Tampa Bay.

Since adverse weather conditions pose major threats to bridge safety, the navigational system designs were primarily compared under two adverse environmental conditions: intense thunderstorms and dense fog.

The major objective of the study was to compare the relative safety of the Sunshine Skyway Bridge as a function of Navigational System Designs and Environmental Conditions.

EXPERIMENTAL METHODOLOGY

Participants

Seven pilots from the Tampa Bay Pilots Association participated in the study.

Models of Tampa Bay

Three separate simulation models of Tampa Bay were developed in order to simulate the four navigational system designs under investigation. Navigational System Designs 2 and 3 differed only in the availability to the pilot of a precision electronic navigation aid and, therefore, the same simulation model of Tampa Bay was used for both designs.

Each model of Tampa Bay required the construction of five data bases: *visual, radar, situation display, plotting,* and depth/current/bank (DCB) data bases. These data bases were constructed from information collected from several sources. The data bases were integrated to yield an accurate, unified representation of each model of Tampa Bay.

Ownship Model

Two considerations went into determining the best vessel model to be used in this study. First, the vessel modelled should be at least as large as the largest ship currently calling on Tampa Bay since in general a large vessel poses a greater safety risk than a small vessel. The largest vessels to have used the port thus far are in the 112,000 to 126,000 DWT class. It was considered desirable to use a slightly larger vessel in anticipation of potentially larger vessels which can be expected in the future when the current channel widening and deepening project is completed. The second consideration was that the vessel should be responsive to wind effects since strong and variable winds pose safety risks for vessels in Tampa Bay.

The vessel chosen to meet these considerations was a light (unloaded) 165,000 DWT tanker. The tanker was modelled to be approximately 951 feet long, 155 feet wide with a light draft of 28 feet. This tanker is slightly larger than the largest ship currently passing under the Sunshine Skyway Bridge. This insured that the results of the study include an adequate margin of safety for smaller ships currently using the port and large ships which Tampa Bay may see in the near future.

Since the vessel was modelled as unloaded, it was much more influenced by wind due to its greater sail area (freeboard) compared with a loaded tanker. An additional consideration was that most of the collisions between ships and the Sunshine Skyway Bridge have involved light vessels, e.g., the M/V SUMMIT VENTURE.

The bridge of ownship was equipped with standard instrumentation composed of actual marine hardware like that found aboard large merchant vessels (see Table 3). In addition to standard equipment, a Precision Electronic Navigation Aid (PENA) was made available for certain passages. PENA was modelled to represent a generic precision positioning system providing both analog and digital information. The specific source of position information, e.g., LORAN signal, cable, etc., was not of concern in this study. Therefore, when available the PENA functioned properly and was not influenced by thunderstorm activity, bridge structures, or any other factors that might influence any one specific system.

Experimental Design

The two variables (factors) examined were Navigational System Design and Environmental Condition. The four navigational system designs were previously described. There were three environmental conditions examined: favorable, intense thunderstorm, and heavy fog. They were characterized by specific combinations of current, wind, and visibility.

1. Favorable Condition

- Current-slack
- Winds-8 knots from 285°T ± 45°
- Visibility - Clear 12 nm

2. Intense Thunderstorm Condition

- Current - 2 knots flood/fair current
- Wind - Mean of 40 knots with gusts ± 10 knots from 330°T ± 45°
- Visibility - restricted to approximately 0.1 nautical mile due to heavy rain which also produced a high degree of rain clutter in the radar presentation

3. Heavy Fog Condition

- Current - 2 knots flood/fair current
- Wind - 8 knots from 285°T ± 45°
- Visibility - restricted to approximately 0.1 nautical mile with no effect on radar

The two variables were combined to produce nine experimental conditions. Each of the four navigational system designs was investigated under both thunderstorm and fog conditions resulting in a total of eight experimental conditions. The favorable environment was combined with Navigational System Design 1 only. This condition was used as an estimate of performance under what would generally be considered "safe" conditions. The alternative designs under adverse conditions were compared with this last condition in order to determine whether they approximated or exceeded this safe condition. (See paragraph 4.3.3 of the report for a complete description of the logic of these comparisons).

Scenario Design

The nine experimental conditions investigated in this study gave rise to nine scenarios. In addition, two scenarios were designed to provide simulator familiarization to the pilots. Each pilot, therefore, experienced a total of eleven scenarios. The scenarios were labeled from 1 through 9, corresponding to experimental conditions 1 through 9, and the familiarization scenarios were labeled A and B.

For all scenarios, pilots had the assistance of a licensed mate and helmsman on the bridge. The mates were required to assist pilots in whatever way the pilots deemed necessary, in the same way as would occur on a merchant vessel. The helmsmen were required to execute pilots' rudder and course commands. In addition to the mate and helmsman, pilots had a "lookout" positioned at the bow during all scenarios where limited visibility would occur, i.e., thunderstorm and fog conditions.

Three scenarios involved Navigational System Design 1 which represented the channel and bridge as they were in May 1980 (Scenarios 1, 2, and 3). For each, the vessel was intialized abeam of Buoy "C15" in the center of Mullet Key Channel and proceeded until it was clear of the bridge (see Figure 1). The Precision Electronic Navigation Aid was not operational during any of these scenarios. Environmental conditions varied from favorable (Scenario 1), to thunder storm (Scenario 2), to fog (Scenario 3) conditions.

For all four scenarios involving Navigational System Designs 2 and 3 representing the old channel and new bridge, the vessel was initialized abeam of buoy "23" in the center of Mullet Key Channel (Scenarios 4, 5, 6, and 7). The runs were terminated when the vessel cleared all bridge structures (see Figure 2). For two scenarios the Precision Electronic Navigation Aid was operational (Scenarios 6 and 7) and for two it was not operational (Scenarios 4 and 5). Finally, two scenarios involved thunderstorm conditions (Scenarios 4 and 6) and two involved fog conditions (Scenarios 5 and 7).

For all scenarios involving Navigational System Design 4, representing the extended Cut A Channel, the initialization position was midway between buoys "19" and "21" in the center of Egmont Channel (Scenarios 8 and 9). These scenarios terminated, as did all other scenarios, when the vessel cleared all bridge structures (see Figure 3). The Precision Navigation Aid was not present for either of these scenarios. The environmental conditions involved thunderstorm (Scenario 8) and fog (Scenario 9) characteristics.

RESULTS AND CONCLUSIONS

To evaluate the relative safety of the environmental conditions and the alternative navigational system designs, three categories of performance measures were analyzed. They were measures of vessel's proximity to bridge structures, vessel controllability and pilot's subjective evaluations.

Findings Regarding the Effects of Environmental Conditions

With respect to the effects of the environmental conditions on bridge safety, it was concluded that the thunderstorm condition was significantly less safe than the fog condition. Average closest point of approach (CPA) was almost 50 feet closer to the bridge in thunderstorm conditions when compared with fog conditions. In fact, all three bridge contacts which occured in the study happened during thunderstorm conditions. The same pattern held for average distance from the bridge although the difference was not statistically significant. In addition to closer vessel proximity to the bridge, thunderstorms produced almost twice as much variability in each vessel transit past the bridge indicating less stable, and less safe, vessel performance. During thunderstorms, therefore, vessels were coming significantly closer to the bridge with significantly greater variability. This pattern was observed for each navigational system design hence there were no significant interactions between environmental conditions and navigational system designs.

The environmental conditions did not have a great effect on vessel controllability measures involving yawing characteristics, rudder activity, or distance from channel centerline. Environmental conditions did, however, significantly affect vessel swept path characteristics. Pilots were required to use greater crab angles during thunderstorm scenarios due to the perturbing influence of high winds.

Finally, pilots rated thunderstorms as requiring more cognitive effort, being more stressful and creating a more difficult task than fog conditions. Pilots also indicated that their workload was higher during thunderstorms.

Findings Regarding the Effects of Navigational System Design

The primary method of evaluating the relative safety of the various navigational system designs was to compare them with respect to measures of vessel proximity to bridge structures. These measures of proximity were examined: closest point of approach (CPA) to bridge, average distance of vessel from bridge, and variation of average distance from bridge. The navigational system designs were found to significantly differ with respect to the first two of these three variables.

Navigational System Design 3 (NSD3), which incorporated the precision electronic navigation aid, produced larger values for both CPA and average distance than any other design. Generally NSD2 and NSD4 were found not to differ significantly on these variables. When the precision aid was used, CPA's averaged almost 78 feet larger than in the other two alternatives and the average distance from the bridge was approximately 80 feet greater. Interestingly, all three alternatives under adverse conditions were superior to NSD1, the 1980 design, under **favorable** conditions. Hence all three alternative designs resulted in increased bridge safety.

Based upon these findings, it can be concluded that the design incorporating the precision navigation aid provided for the greatest degree of bridge safety of the designs examined in this study. Comparing all designs simultaneously, it can be concluded that the relocation and redesign (greater horizontal clearance) of the Sunshine Skyway Bridge will result in greater bridge safety when compared with the 1980 design (NSD2 under adverse conditions was superior to NSD1 under favorable conditions). Including a precision navigation system along with the relocation and redesign of the bridge provides even greater bridge safety (NSD3 was superior to NSD2). Note that the only difference between NSD2 and NSD3 was the availability of precision navigation information in the latter.

It can be further concluded that, under the conditions studied, the extended Cut A Channel design (NSD4) provided no added margin of safety beyond the bridge relocation and redesign. The only difference between NSD2 and NSD4 was the location of the turn into Cut A Channel relative to the bridge. In the evaluation of proximity variables, NSD2 and NSD4 differed little. Hence, the relocation of the turn was not found to add to bridge safety. In fact, the only two bridge contacts which occurred in the alternative navigational system designs occurred in the extended Cut A Channel design, where the entire portion of the transit under thunderstorm conditions was after the turn. Several pilots commented that in the absence of visual cues they preferred to make a turning maneuver when wind was affecting their vessel rather than attempting to maintain a perfectly straight course. They indicated that the presence of the turn aided them in position estimation, whereas without the turn similar "sense of position" information was lacking.

The superiority of the precision navigational aid design can be attributed to the finding that, based upon the analysis of vessel controllability measures, the position information provided by the aid enabled the pilots to engage in increased vessel maneuvering in an effort to safely transit the bridge. The increase in piloted maneuvering of vessels with precision navigation information observed in this study is consistent with other studies of such aids available in the literature.

In addition to the objective evidence for increased bridge safety with the PENA, pilots' subjective evaluations of the aid were very positive. All seven pilots in the study indicated that it would be a useful aid to decision making in Tampa Bay, especially during periods of limited visibility.

RECOMMENDATIONS

Based upon the results of this study and discussions with Tampa Bay pilots who participated in the simulation, the following recommendations are offered.

Recommendation 1

The development and implementation of a precision electronic navigation aid for the pilotage of vessels in Tampa Bay should be supported. The findings of this study provided scientific evidence of increased safety of the replacement Sunshine Skyway Bridge when such an aid was used by Tampa Bay pilots to make simulated bridge passages under extremely adverse weather conditions.

Recommendation 2

The development and implementation of plans to extend Cut A Channel seaward in an effort to move the turn further away from the new Sunshine Skyway Bridge should not be supported. The results of this study provided no evidence of increased bridge safety as a result of movement of the turn.

Recommendation 3

Based upon discussions with the Tampa Bay pilots who participated in the study concerning vessel transportation needs in the vicinity of the bridge, it is recommended that additional consideration be given to the creation of anchorage areas seaward of the bridge.

CHAPTER 1

INTRODUCTION

The Sunshine Skyway Bridge extends across the southern end of the Tampa Bay connecting Manatee County and Pinellas County, Florida. In May of 1980, a large portion of the bridge's western span was destroyed as the result of the impact from a large vessel which strayed from the ship channel during an intense thunderstorm. In addition to extensive monetary losses, 35 lives were lost in the accident.

Rather than repair the existing damaged span, a replacement bridge will be built adjacent to the location of the existing structure. The Florida Department of Transportation (FDOT) has spearheaded a comprehensive risk management and engineering design effort to ensure that the replacement Sunshine Skyway Bridge is part of an overall bridge and waterway system design that minimizes the likelihood of future vessel-bridge collisions.

The study to be described in this report was a part of that risk management effort. It utilized the U.S. Maritime Administration's Computer Aided Operations Research Facility (CAORF) which houses a real-time, full-mission shiphandling simulator to examine the relative safety of several "navigational system designs" incorporating the Sunshine Skyway Bridge. (A description of the CAORF simulator can be found in Appendix A). As the term is being used here, "navigational system design" refers to the specific configurations of bridges, channels, aids to navigation, and shipboard navigation aids under investigation. That is, a channel design, configuration of aids to navigation, presence or absence of special shipboard navigation aids, and presence of the old or replacement Skyway Bridge constituted a navigational system design. The study examined the operational safety of several such system designs under a variety of environmental conditions using real time man-in-the-loop simulation. The men-in-the-loop were seven Tampa Bay pilots. The study, therefore, represented an effort to mitigate the risk of future vessel-bridge incidents.

This is described in detail in the following sections of this report. Chapter 2 will provide background information relating to vessel interactions with bridges in general, and specifically risk mitigation efforts related to the Sunshine Skyway Bridge. Chapter 3 presents the objectives of the study and Chapter 4 details the experimental methodology. The results are presented in Chapter 5 and the conclusions and recommendations in Chapter 6.

CHAPTER 2

BACKGROUND INFORMATION

2.1 DESCRIPTION OF THE TAMPA BAY AREA AND THE RISKS TO THE SUNSHINE SKYWAY BRIDGE

Tampa Bay is located on Florida's western coast approximately 230 nautical miles north of Key West and in about the middle of the state along the north-south dimension. The Bay averages about 6.5 miles wide and 20 miles long. From its opening in the Gulf of Mexico, the Bay extends in a north-northeasterly direction.

Tampa Bay provides access to several ports of which Port Tampa and Port Manatee are the largest. A range of commercial vessel types pass through the Bay including tankers and dry bulk carriers, freighters and containerships, and barges. While the majority of these vessels are below 50,000 DWT, vessels in the 126,000 DWT class have used port facilities in Tampa Bay. The Bay handles a high level of vessel traffic with the total number of vessels and barges (registered only) passing one way estimated to be over 4,000 in 1980 (Greiner Engineering Sciences, Inc., 1982). In the future, the size of vessels in Tampa Bay can be expected to increase. Economic pressures within the ports, economies of scale which offer a reduction in operating costs per unit of cargo, and improvement in ship construction technology encourage ship operators to use larger vessels. The size of vessels entering the Port of Tampa, for example, has increased from a maximum of 15,000 DWT in 1950 to 120,000 DWT today. Even larger ships with 150 foot beams can easily be projected for 1985 when channel widening and deepening projects should be completed.

Large vessels enter Tampa Bay from the Gulf of Mexico through Egmont Channel. This channel passes between Egmont Key, where the pilot station is located, and Mullet Key. Egmont Channel has a charted depth (NOAA Chart 11412, 27th Ed., 1982) of 36 feet, width of 600 feet, and extends for approximately 3.9 nautical miles. Less than one mile east of the lower tip of Mullet Key, Egmont Channel intersects with Mullet Key Channel. This channel segment lies on a heading of 081°T and has a charted depth of 34 feet, width of 500 feet, and length of 2.9 nm. Beyond Mullet Key Channel is a series of channel cuts which extend throughout the Bay and connect the ports of Tampa Bay with the Gulf. The first of these cuts, Cut A Channel, brings vessels under the Sunshine Skyway Bridge. Cut A Channel lies on a heading of 062°T requiring a turn of approximately 18 degrees from Mullet Key Channel. Cut A Channel has a charted depth of 34 feet, width of 400 feet, and length of 2.7 nm. The Sunshine Skyway Bridge crosses Cut A Channel approximately 0.7 nm following the 18 degree turn from Mullet Key Channel. Cut A Channel joins Cut B Channel, the next channel segment, to form a 24 degree angle. Cut B and subsequent channel cuts have charted dimensions of approximately 400 feet wide and 34 feet deep while their lengths vary from about 1.5 nm to 3.5 nm.

The Sunshine Skyway Bridge is a twin span structure which is 27,373 feet long and extends across the Bay connecting Manatee County with Pinellas County. The bridge provides for 800 feet horizontal clearance and 149 feet vertical clearance for vessel traffic. Currently only the eastern span of the bridge is available as a two lane highway serving as part of Interstate 275. The western span was eliminated from the highway system as a result of an accident which occurred on the morning of May 6, 1980.

The Liberian bulk carrier M/V SUMMIT VENTURE was making its way inbound to Rockport Terminal in Tampa Bay. The 34,000 DWT vessel was 609 feet long, 85 feet in beam and at a light draft of 9.4 feet forward and 21.5 feet aft. There was about 35 feet of freeboard amidships. The vessel encountered an intense thunderstorm as it approached the 18 degree turn from Mullet Key Channel to Cut A Channel just 0.7 nm before the bridge. The winds were estimated to be around 60 knots and the rain was so intense that visibility was near zero and the ship's radar presentations were severely rain cluttered. Having insufficient perceptual cues to determine the vessel's precise location but concluding that it was too late to abort the transit, the vessel's pilot decided to attempt to make the bridge passage. At about 0734 e.d.t. the vessel struck a support pier of the western span and approximately 1300 feet of the bridge collapsed into the bay. As a result of the accident, 35 persons who where in motor vehicles died, millions of dollars worth of damage was done to the bridge, and one million dollars worth of damage was done to the SUMMIT VENTURE.

Following the investigation of the incident, the National Transportation Safety Board (1981) concluded that the probable cause of the accident was the severe weather conditions, the lack of a severe weather warning to mariners by the National Weather Service, and "the failure of the pilot to abandon the transit when visual and radar navigational references for the channel and bridge were lost in the heavy rain". The United States Coast Guard (1982) investigation of the accident came to the same general conclusions regarding the probable causes.

Several conclusions concerning the risks to the safety of the design of the waterways in Tampa Bay emerged from both investigations. One was that the system of aids to navigation in use at the time of the accident was inadequate. Conclusion 14 in the USCG report (1982) stated that "the current short range aids to navigation system installed in the Tampa Bay area (pairs of turn buoys) appears adequate only for visual navigation with traffic density and ship sizes of ten years ago" (p. 24). The NTSB (1981) concluded that electronic navigation aids may "provide significantly improved navigational data" to pilots (p. 41). In addition, the NTSB concluded that the turn from Mullet Key Channel to Cut A Channel is too close to the Sunshine Skyway Bridge to safely abort improper turns. The Board noted that "channel bends should not be so close to bridges that the success of navigating under the bridge span is dependent on the successful navigation of the channel bend" (p. 35).

Since the accident, several changes have been made or are planned for Tampa Bay. These include changes to the system of aids to navigation, the design of the Sunshine Skyway Bridge, and the channel dimensions in the Bay.

Since 1981, the USCG has implemented many changes to the floating aids to navigation. Unlighted buoys in the vicinity of the bridge were replaced with lighted bouys and buoys were added so that all bends are now marked with three lighted aids. The midpoints of Mullet Key Channel and Cut A Channel are now marked by lighted gated buoys. Most buoys are equipped with radar reflectors and the Coast Guard is continuing to convert those not so equipped. Terrestrial ranges mark the centerlines of all ship channels near the bridge.

As a supplement to these improved aids to navigation, the decision was made to evaluate the feasibility of providing increased safety for bridge passage by including a precision electronic positioning system as a navigational aid to pilots. Such a system would provide accurate information with regard to a vessel's position in a channel. Since this type of system is of central concern in the present investigation, it will be discussed in greater detail in later sections of this report.

In addition to improvement in aids to navigation, the decision was made by the Florida Department of Transportation to replace the original Sunshine Skyway Bridge with a new bridge. Several changes are planned in the bridge design to make it safer for passage by vessel traffic. The new cable-stayed structure will be situated 1015 feet to the northeast of the original bridge thus increasing its distance from the turn from Mullet Key Channel to Cut A Channel to approximately .9 nm. The horizontal distance between the supporting tower piers will be increased from 800 to 1200 feet. The vertical clearance will be increased from 149 to 175 feet. In addition to the increased distance from the turn and horizontal and vertical clearances, a bridge pier protection system is planned. The favored plan would combine dolphins, complete island and horseshoe island stuctures. Each of the main bridge piers immediately adjacent to the ship channel would be protected by an island which completely encircles the pier. In addition, a 60 foot diameter dolphin would be placed to the north and south of each island. The next two bridge piers on either side would be protected by a horseshoe shaped island. Hence a total of six piers, three on either side of the ship channel, would be protected. With such a pier protection system it is expected that an errant vessel would ground on the protection islands prior to making contact with any of the bridge piers (Greiner Engineering Sciences, Inc., 1982). Appendix B contains illustrations comparing the replacement bridge design with the old bridge design, the relative positions of the replacement and old bridges, and the pier protection system.

Another factor which may have an impact on bridge safety is the design of channel approaches to the new bridge. Maintenance and improvements of the channels in Tampa Bay are the responsibility of the U.S. Army Corps of Engineers. The COE is executing a channel widening and deepening project which will bring the controlling depth in the main ship channels in Tampa Bay from 34 to approximately 44 feet (U.S.A. COE, 1979). In the vicinity of the bridge, the channel widths have been increased approximately 100 feet: Egmont Channel to 700 feet, Mullet Key Channel to 600 feet, and Cut A Channel to 500 feet. The project includes wideners or "cutoff turns" at the intersections of Mullet Key and Cut A Channels and Cut A and Cut B Channels. These wideners, particularly at the 18 degree turn from Mullet Key Channel into Cut A Channel, provide greater clearance for vessels negotiating these turns. The wideners are marked by two flashing buoys at the ends of the wideners and a single buoy on the point side. These channel improvements had actually been completed at the time of the SUMMIT VENTURE incident. However, since the dredging project is as yet incomplete, buoyage in these channels remains in locations marking the prior more narrow channel width and not the widened channels.

Every effort is being made by the Florida Department of Transportation to minimize the risks to the replacement Sunshine Skyway Bridge. As part of its efforts, FDOT initiated this study the aim of which was to examine the relative safety of several alternative risk mitigation plans in terms of the human operation and navigation of large vessels in the vicinity of the bridge.

The nature of vessel-bridge interactions in general and of risk mitigation plans for the replacement Skyway Bridge will be elaborated in the sections which follow.

2.2 RESEARCH ON VESSEL COLLISIONS WITH BRIDGES

2.2.1 A System Design Approach

The effort to minimize the potential of vessel collisions with the Sunshine Skyway Bridge requires the identification of those factors which pose the greatest threats to bridge safety. Identification of relevant threat factors is aided by an examination of research on vessel collisions with bridges. In this section, research on those factors identified as threats to the safe passage of vessels under bridges is considered.

The framework in which this research was viewed can be considered a system design approach. The safety of a bridge is considered as part of an overall system. The components of the system are included in Table 1. Important factors are organized into several major categories including bridge characteristics, waterway characteristics, aids to navigation, vessel characteristics, operator characteristics, traffic conditions, and miscellaneous other factors. The approach taken here is that it is the interaction of these components as a single system rather than any one single factor in isolation which influences bridge safety. Hence, the design of the entire system is of major importance. When vessel transit through a bridge is of primary concern the term "navigational system design" can be used to emphasize the focus on the system's design for vessel navigation.

While a lack of bridge safety may result from any one of these components, some factors may be seen as being more critical than others. Critical factors must however, interact with the others to result in safe or unsafe conditions.

The SUMMIT VENTURE accident serves to illustrate this point. The primary causes of the accident, according to the NTSB (1981), were severe weather (an environmental characteristic) and pilot failure to terminate the bridge passage (an operator characteristic). However, the absence of bridge safety in that situation was also a function of bridge characteristics, the horizontal clearance and lack of a sufficient pier protection system; waterway characteristics, the need for a turn less than one mile before the bridge; vessel characteristics, the light loading condition which resulted in a draft small enough to permit the vessel to sail out of the channel; aids to navigation, the failure of the available aids to provide the pilot with accurate position information; and traffic conditions, the presence of another vessel headed outbound from the other side of the bridge.

In the SUMMIT VENTURE case, all these factors and many others contributed to the failure of the pilot to make a safe passage under the bridge. The identification of those components in the system having the greatest impact on bridge safety is an important first step in minimizing the risk associated with vessel-bridge interactions.

The second step is to make an effort to control those components in a way that will maximize safe vessel transit. These two steps will be examined in subsequent sections of this report.

2.2.2 Critical Factors in Vessel Collisions with Bridges

In a study of commercial vessel collisions in U.S. waters, the National Transportation Safety Board (1972) found that vessel collisions with bridges were the most frequent type of collision observed. Between the years of 1966 and

TABLE 1. MAJOR COMPONENTS IN A SYSTEM APPROACH TO BRIDGE SAFETY FROM VESSEL COLLISION

Bridge Characteristics

- Horizontal and vertical clearances for vessel passage
- Structural integrity against vessel impact
- Pier protection system designed to protect the bridge from errant vessels
- Navigational markings (see Aids to Navigation below)

Waterway Characteristics

- Channel Geometry including depth, width, and bank slope
- Channel configurations including the layout of straight segments and turns in the vicinity of the bridge
- Depths of waters outside the channel
- Waterway bottom materials, e.g., sand, mud, rock, etc.

Aids to Navigation

- Channel boundary markings, e.g., buoys and beacons
- Channel centerline markings, e.g., ranges
- Bridge navigational markings, e.g., bridge lights
- Navigation Aids, e.g., pilot carried precision navigation aids
- Informal Navigation Aids, e.g., shore structures

Vessel Characteristics

- Vessel type
- Vessel dimensions such as length, beam, and draft
- Loading characteristics, e.g., degree of loading and trim
- Maneuvering characteristics
- Equipment

Environmental Characteristics

- Wind
- Current
- Ambient Lighting
- Visibility
- Weather

Operator Characteristics

- Skill and Training
- Familiarity with the waterway and the vessel type
- Temporary states such as fatigue, distraction, etc.
- Overall workload and stress

Traffic Conditions

- Traffic volume and characteristics
- Types of meeting situations in the vicinity of the bridge
- Vessel traffic service

Other Characteristics

- Background lighting
- Other structures in the waterway which make radar detection and identification difficult
- Physical obstructions to visual detection of important objects, such as land masses which may obscure sightings of a bridge after a turn
- Competence of ownship's crew assisting the vessel operator

1970 vessel collisions with bridges accounted for 42 percent of the collisions examined. In addition, the National Academy of Sciences has reported an annual increase in serious collisions from the period of 1960 to 1970, and 1971 to 1982 (National Research Council, 1983). As the size and mass of vessels have become progressively greater, the consequences of ship collisions with bridges have also become greater. As Gardenier noted, "Increasingly....ships tend themselves to be ponderous behemoths of masses and momentums against which virtually no bridge can stand" (1983, p. 78). Reviews of recent accidents (e.g., Frandsen, 1983) have supported that claim.

Given the severe consequences to life and property of vessel collisions with bridges, research into the major factors responsible for those collisions is of utmost importance.

The National Transportation Safety Board (1972) study mentioned earlier reviewed the primary causes of vessel collisions in general (not specifically with bridges). The Board determined that 84 percent of the collisions examined resulted from some form of human error (personal fault and errors in judgment).

The identification of human error as the predominant cause of vessel collisions has been made by many other reviewers as well (Gardenier, 1983; Larsen, 1983; Mikkelson, 1983; MTRB, 1976; Paramore, Keith, King, Porricelli, and Willis, 1979).

By itself the term "human error" in not particularly explanatory. When efforts are made to break down human error into its component parts, the interaction between the human operator and the other factors in the "bridge safety system" become apparent. It must be emphasized, however, that the use of the term "human error" is quite unfortunate since it tends to suggest fault with the human operator. A better term would perhaps be "human factors" since it tends to be more neutral and better expresses the notion that the human operator is one factor in a larger system. Paramore et al. (1979b) have effectively argued that "Even the most alert and skillful operator lacks the means to guarantee control in some very common situations. It is neither fair nor productive to talk about human error as necessarily or even usually a matter of personnel deficiency. Rather, the focus is properly on the total situation and factors in the situation which strain reasonable performance capabilities and reduce the reliability of human performance in vessel control" (p. 1-3).

The operator is, however, a critical factor and his executive control of the entire system will be discussed at greater length in the next sections on the Operator Control Model. For the purposes of the following discussion, the term "human error" will continue to be used since it prevails in the literature.

The NTSB (1972) listed the twelve most frequent contributing factors to human error. Of these factors, eight were directly related to navigation and safety issues. "Such factors as restricted channels, congested docks and pier areas, currents and tides, navigation signals, adverse weather, and poor visibility, create added stresses that are placed upon the operator" (p. 7). The NTSB noted that these factors add to the already complex decision making required of the mariner.

In 1976, the MTRB published a comprehensive study of human error in merchant marine safety performed by a special panel created to explore the problem. The panel defined human error as "the commission or omission of acts by maritime personnel that cause or contribute to merchant marine casualties or near-casualties" (p. 7). A total of 14 factors were identified as contributors to human error. These factors are listed in Table 2. Inspection of the factors listed in the Table, as well as those identified in the 1972 NTSB study, illustrates the interaction between human factors and other characteristics of the overall system in which bridge safety is defined, e.g., adverse weather and inadequate aids to navigation. Generally, human errors are errors of omission or commission emerging from the interaction of the operator's behavior with various aspects of his environment. It is, therefore, difficult to identify which single cause is responsible.

In addition to human error, the second most critical factor contributing to vessel collisions with bridges is the environment. The NTSB (1972) identified "storms — adverse weather" as one of the primary causes of collisions. Regarding adverse weather, wind and limited visibility are the major contributing factors (Payton, 1976; Gardenier, 1983; Larsen, 1983; Paramore et al. 1979a; Paramore et al. 1979b). Another major environmental factor was current. Paramore et al. (1979) cited current as the most frequently identified casual factor in rammings and groundings. Paramore et al. (1979b) found that cross currents and winds were especially problematic when making a bridge passage close to a turn in a channel. Their effects were seen to create operator control problems resulting in loss of vessel control or misalignment. Following currents were also found to be problematic. Currents and winds have

TABLE 2. FACTORS IDENTIFIED BY THE MARITIME TRANSPORTATION RESEARCH BOARD (1976) AS CONTRIBUTING TO HUMAN ERROR

1. Inattention (lack of full vigilance to the duties and responsibilities)
2. Ambiguous Pilot-Master Relationship
3. Inefficient Vessel Bridge Design (poor instrumentation and layout on the bridge)
4. Poor Operational Procedures
5. Poor Physical Fitness
6. Poor Eyesight
7. Excessive Fatigue
8. Excessive Alcohol Use
9. Excessive Personnel Turnover
10. High Levels of Calculated Risk
11. Inadequate Lights and Markers
12. Misuse of Radar
13. Uncertain Use of Sound Signals
14. Inadequacies of the Rules of the Road

also been found to be major factors in bridge and towboat collisions with bridges across inland waters (Dayton, 1976).

While human error and environmental conditions constitute the major factors contributing the ship collisions with bridges, several other factors have been noted as well. Bridge proximity to channel bends and bridge characteristics, e.g., relation between the size of the bridge span and vessel size, have been noted in several reviews (e.g., Gardenier, 1983; Paramore et al., 1979a and 1979b). Paramore et al. (1979b) found that 27 percent of collisions, groundings, and rammings occurred in sharp turns. In that study, sharp was defined as greater than 20 degrees. Paramore et al. (1979a) found that 65 percent of accidents at a bridge or lock occurred within 0.5 mile of a bend. Other factors often cited in ship collisions with other objects relate to the ease with which the vessel operator can acquire needed information. These include the configuration and quality of aids to navigation, the availability and quality of shipboard equipment, and the communication of critical environmental information to the vessel operator. The latter was mentioned as a contributing factor in the SUMMIT VENTURE accident (NTSB, 1981) and has been found to be a major problem in towboat collisions (Paramore et al., 1979a). In addition, Paramore et al. (1979b) noted that three major problems identified in the analysis of collisions, groundings, and rammings were (1) poor vessel to vessel communications, (2) poor detection and monitoring of the position of other vessels, and (3) failure to maintain proper navigational position, particularly when wind and current effects were strong.

While all of the factors listed in Table 1 can contribute to vessel collisions with bridges, the human operators, the environment, and characteristics of ships, bridges, and waterways are of major importance. Furthermore, it appears that the interaction of these factors with the human operator is of primary concern. The reason for this emphasis on the interaction between design factors and the human operator will be elaborated in the next section.

2.2.3 The Operator Control Model of the Navigational System Design

It has been suggested that the factors involved in vessel collisions with bridges represent components of an overall system design. In addition, human errors, or more appropriately human factors, have been identified as primary causes of collisions. The overall organization of system design components and the major contribution of human factors to the overall safety of bridges spanning navigable waters can be interpreted within an operator control model.

Such a model places the operator as the primary controller or executive of the overall system. The model is presented in Figure 1. The model is divided into three levels: Input Factors, Operator Characteristics, and Vessel Performance. Most of the components in the bridge safety system defined in Table 1 fall in the level of input factors. These factors provide information which serves as input to the operator whose primary task is to safely maintain control of his vessel.

The operator must perceive, interpret and integrate these inputs in order to make appropriate control decisions. The

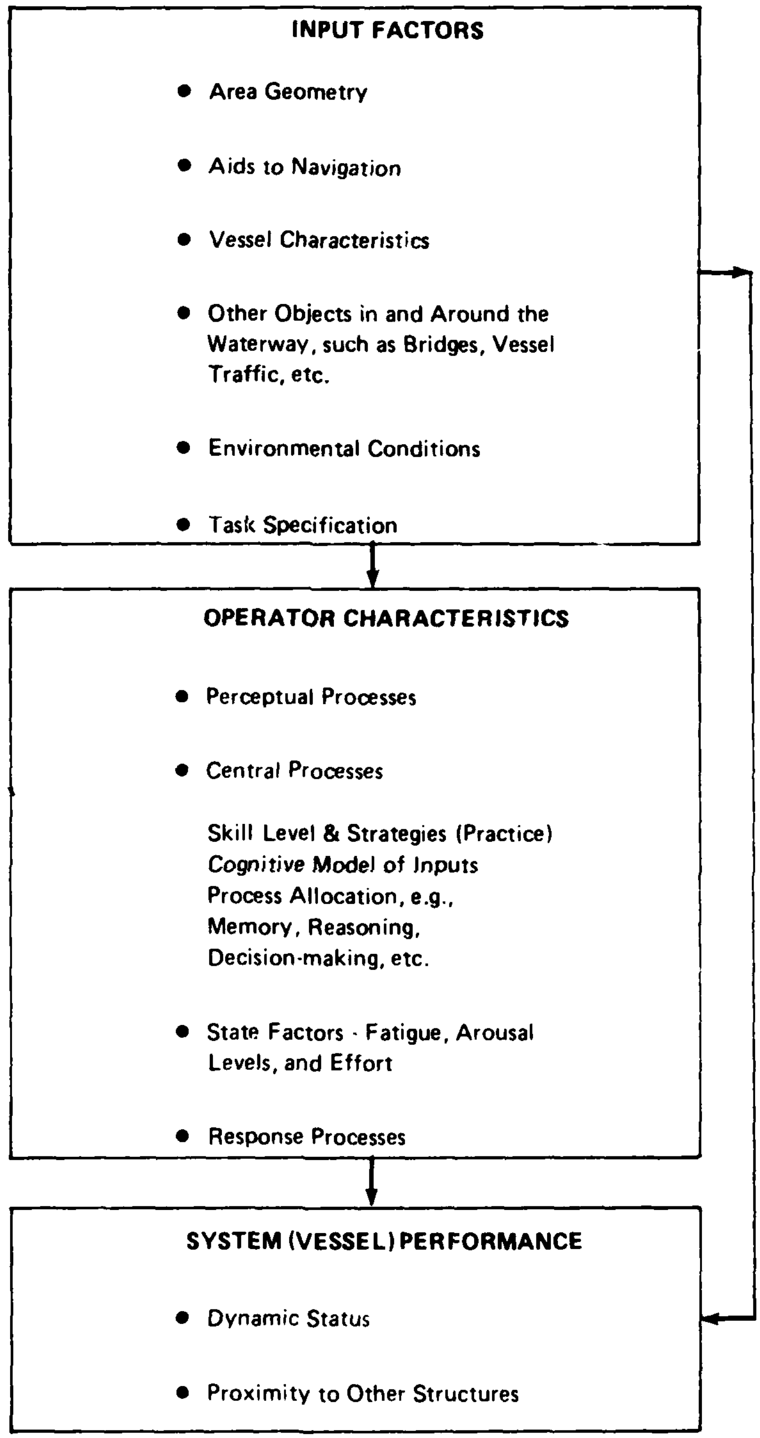


Figure 1. A "Operator-In-The-Loop" Model of an Operator Control System (In this Case a Vessel). As the Operator Loses Control, the Vessel Becomes More Controlled by the Input Factors Directly (Represented by the Dashed Line).

operator's ability to safely control a vessel is based on many factors. First, the input information must be available to him. Insufficient information can result from (1) a deficiency of cues in the environment due to factors such as a lack of suitable aids to navigation, adverse weather limiting visibility and other available inputs, or poor instrumentation aboard the vessel; (2) physical states of the operator, such as poor health or fatigue; and (3) workload, stress and time pressures which limit the operator's time and capacity to perceive and assimilate necessary information. Second, once information is obtained, the operator must decide on a control action, e.g., to apply a certain amount of rudder to achieve a desired course-made-good. Having sufficient information on which to base decisions does not guarantee that an appropriate decision will be made. The operator must know how to integrate and interpret information. In addition, the operator must possess an accurate understanding of his vessel's response and maneuvering characteristics. Factors such as the operator's skill and training become important here. Third, once a decision is made, the operator must issue the appropriate command and he and his crew must correctly execute the command.

Finally, the operator's interpretation of the situation, i.e., the position of his vessel, the forces acting on the vessel, its maneuvering characteristics, and the required vessel control action, results in a specific course of behavior of the vessel with respect to bridge safety. The performance of primary interest is the vessel's proximity to bridge structures. The resulting vessel performance is the end product of an integration of all components of the system as they are channeled through the operator (see Figure 1). Thus the operator can be described as being in control or being the executive of the entire system, hence the term operator control model.

The above should not be interpreted as suggesting that the operator is always in total and complete control of the system. Mechanical failure, crew errors, extremely perturbing outside forces, unanticipated circumstances such as submerged debris, etc. can all minimize the direct influence of the operator over the performance of his vessel.

Viewed within an operator control framework, the predominance of human error as a causal factor in vessel collisions with bridges is understandable. However, the operator depends on many components of the entire system design for information needed to safely control his vessel. Even the competent operator must have sufficient information from and about his environment to make appropriate decisions. On the other hand, the operator must fully understand the situation that his vessel is in in order to make proper decisions. If the operator is poorly trained, lacks sufficient knowledge about the maneuvering characteristics of his vessel, or is impaired due to some transient physical state such as fatigue or intoxication, even an abundance of accurate information from the environment may not result in a safe vessel transit.

2.2.4 Mitigation of the Risks Associated with Vessel-Bridge Collisions

The causal factors identified in the study of vessel collisions with bridges has often emphasized the important role of the mariner and the human factors involved in the operation and control of vessels. It follows, therefore, that efforts to mitigate these problems will mainly, although not exclusively, focus on the vessel operator (NTRB, 1981). A study recently completed by the Committee on Ship-Bridge Collisions of the National Research Council (1983) examined the mitigation of risks associated with vessel collisions with bridges. The committee studied major collisions involving bridges spanning major coastal ports and navigational channels of the United States. Their recommendations regarding preventative actions were organized into three categories of factors: shipboard, external, and environmental. Included in shipboard factors were (1) the qualifications and training of vessel operators, and (2) the improvement of shipboard equipment, especially precision navigation systems and radio communications between vessel and bridge personnel. The development of accurate precision Loran-C navigation systems was seen as particularly promising.

External factors included (1) bridge characteristics, especially markings and locations, (2) aids to navigation to provide accurate and reliable position information, and (3) marine traffic engineering, such as vessel traffic services. The determination of exact vessel positioning was again stressed. In the report, the Committee stated that it is therefore "imperative that aids to navigation be placed so that pilots of larger ships can accurately determine not only the ship's position but that of all vessel extremities in relation to the channel—and to the sometimes narrower channel boundaries at the bridge—in sufficient time to shape up safely" (1983, p. 75).

Knowledge of one's position is not always enough. A bridge's location with respect to the channel is an important factor. The committee emphasized the need to provide adequate distance for the least maneuverable vessel transiting a waterway to shape up prior to bridge passage. Turns placed very close to a bridge can be problematic as can bridges which do not cross the channel at right angles.

The final category, environmental factors, emphasized the communication of critical information about the environment to the mariner. The committee concluded that failure to transmit properly and in a timely manner information about conditions such as currents and winds caused a "reduction of the margin of safety in navigational decision making".

These basic categories of potential mitigation factors have been presented in other analyses of vessel-bridge collisions as well. A National Transportation Safety Board study (1972) identified shore based vessel control systems, radio communications, shipboard equipment improvements, precision position determination systems, and improved vessel operator training as areas in which solutions to collisions can be found. Paramore et al. (1979a and 1979b) cited (1) environmental factors including bridge characteristics and channel alignments, (2) vessel and equipment improvements including navigation position information, and (3) personnel training and procedural improvements, including vessel to vessel communication systems.

Considering all these studies together, one can organize these mitigation factors into three basic categories:

- Bridge, Channel, and Environmental Geometry – bridges should provide for maximum horizontal and vertical clearances given the channel geometry around the bridge and the local environmental conditions, e.g., cross-currents, winds, etc.

- Information Systems – the vessel operator should have sufficient timely, accurate and reliable information to allow for safe vessel control operations. This would include providing for bridge marking, aids to navigation marking channels, precision electronic navigation systems and other onboard systems such as radar and CAS, and vessel to vessel communications to permit accurate exchange of information regarding other vessels' intentions.

- Operator Training – the vessel operator requires knowledge of vessel maneuvering characteristics and emergency maneuvers, as well as knowledge regarding use of the vessel's instrumentation.

Given that the bridge and channel geometry provide for enough vessel maneuvering room to permit safe vessel passage, it is up to the vessel operator to collect and interpret navigation information and to integrate this information with his knowledge of his vessel to make a safe bridge passage.

The development of the new generation of precision electronic navigation aids is especially promising as a mitigation factor in vessel bridge collisions. These systems, which provide a rich source of navigation information to the mariner, will be considered next.

2.2.5 Precision Electronic Navigation Aids

In the study of commercial vessel collisions in the United States waters discussed earlier, the National Transportation Safety Board (1972) found that vessel collisions with bridges were the most frequent type of collision observed, accounting for 42 percent of the collisions occurring between the years 1966 through 1970. The predominant cause of the collisions was found to be human error (personal fault and errors in judgement), which accounted for 84 percent of the identified causes. A breakdown of human error into component factors indicated that eight of the twelve factors were related to navigation and safety. The NTSB noted that "these factors ....not only reflect the need to assist the mariner in his complex decision-making processes, but also provide the basis for determining the fundamental functions and requirements for a complete system which can effectively provide collision avoidance assistance" (1972, p. 7). The NTSB recommended "accurate position determination systems" as one of the solutions to the problem of vessel collisions with other structures.

Successful transit of a waterway and, therefore, the safety of structures positioned within that waterway, are dependent upon a pilot's accurate knowledge of the position of his vessel. Accurate knowledge of one's position is a necessary, but not a sufficient, requisite for safe navigation. It is necessary because in order to remain within channel bounds and avoid structures such as bridge piers, a mariner must be aware of his vessel's position with respect to those objects. It is insufficient because, in addition to knowing his position, the pilot must exercise appropriate control over his vessel to keep it safely away from those objects. It is possible to know where one is and still run aground or hit a bridge because of incorrect decision-making, equipment failures, failures to properly execute orders, etc.

In a discussion of electronic navigation aids, this distinction between necessary and sufficient must be emphasized.

These aids provide position information only. They do not make shiphandling decisions or guarantee safe vessel transit. They merely provide information to the mariner who must then integrate that information with other sources of information and make operator control decisions which result in safe operation of his vessel. The value of precision navigation systems must be considered with a human factors, i.e., man-in-the-loop, context. That is, the safety value of the systems should not only be gauged by the accuracy of the position information they provide, but also by whether those systems improve a pilot's shiphandling performance or at least reduce the degree of uncertainty in his decision-making. A perfectly accurate system would be of little value if pilots could not readily use the information to make rapid decisions. For example, a system which provided very precise information in latitude and longitude form could not be used easily by most mariners rapidly and mentally to identify their exact position (King, 1982).

In a discussion of advanced navigation aids, Hopkin noted that "when aids to navigation are devised there is now a greater awareness of the need to make them compatible with known human limitations, particularly of perception, understanding, memory, attention and information processing" (1983, p. 23). Accordingly, one of the aims of modern advanced navigation systems is to present information "so that more could be assimilated and attended to in a given time".

Determining the position of a vessel is based on the integration of a wide variety of sources which vary with respect to the information they provide in differing environmental conditions. For instance, visual sighting of unlighted buoys and ranges may be adequate for navigation in clear visibility during daylight hours, but less than adequate in evening pilotage. Adding lights to buoys makes them more useful for evening navigation but only when visibility is not too poor. Adding bells or whistles improves the localization of buoys under limited visibility but they can be difficult to precisely locate and identify, particularly when it's windy. Radar aids the location of aids to navigation, particularly at night and limited visibility, but can present problems when signal to noise ratios are low, e.g., in a congested waterway. Radar reflectors and racons aid in radar identification of aids to navigation. When weather conditions are extremely poor, as when an intense thunderstorm is encountered, nearly all information can be lost. Very heavy rain can limit visibility to near zero and produce such a high degree of rain clutter on the radar presentation that radars are rendered nearly useless. At that point, the mariner has lost almost all the information needed to determine his position. Dead reckoning in conjunction with gyro information can be used to estimate position, but this is quite inaccurate especially when precise position information is required as is the case in restricted waterways. Traditional electronic aids such as Loran-C are not of much use at this time since their accuracy is measured in hundreds of feet, which is sufficient for unrestricted waters but is inadequate for restricted waters operations.

The development of precision electronic navigation aids is based on the need to provide mariners with enough accurate information to determine position when other "traditional" aids are inadequate. The use of such systems when conditions are favorable would augment the information which can be derived from these aids. The central concern is for a system which is, in a sense, weather-proof.

A precision navigation system should, at the very least, meet the following criteria:

- It should provide accurate and reliable information as to the vessel's position.
- It should provide information in a form which is easily assimilated by the mariner so that it can be rapidly incorporated into his information processing and decision-making processes.
- It should be able to provide information when the information provided by other traditional aids to navigation is degraded by circumstances such as adverse weather conditions.

In addition to these minimal criteria, there are many pragmatic considerations which will not be addressed here. For example, issues such as whether the systems should be permanently aboard ship or pilot carried, and, if pilot carried, what their weight and power source should be are important concerns but will not be discussed in this report.

Another important issue which will not be discussed in this study is the source from which precise positioning information is calculated. A variety of systems have been or are being developed which derived position information from different sources, such as microwaves, shore-based radar, submerged cable, and Loran-C. A general overview of these systems is provided in the **Preliminary Engineering Report** (Greiner, 1982) for the new Sunshine Skyway Bridge. In the present study, the focus was on a generic electronic positioning aid and its usefulness to the mariner in safe pilotage through the channels of Tampa Bay. As such, the source of information which served as input to the aid was not a specific interest in the study. Rather an evaluation of the value of these types of systems to the pilot attempting to make a safe channel transit under a variety of adverse conditions served as one of the main objectives of the investigation.

It is useful for discussion purposes, however, to describe one such precision electronic navigation aid to illustrate the nature of the information presented. This description should not be considered an endorsement of the aid. It is presented to make subsequent discussions more meaningful. The Precision Intracoastal Loran Translocator (PILOT), an electronic aid developed for the U.S. Coast Guard by the Applied Physics Laboratory at Johns Hopkins University, is based upon input from Loran-C and the ship's gyro. Loran-C, however, was initially developed as a long range aid and not for precision positioning in restricted waters. To adapt Loran-C for use in restricted waters, the navigation aids and other structures in the waterway must be surveyed to determine exact Loran-C time differences (TD's) and the stability of the resulting grid must be analyzed (see Olsen, Ligon, Sedlock, and Isgett, 1980, for a more complete discussion of the PILOT system). These data are stored in a microprocessor along with chartlets of the waterway. The microprocessor then receives input from the vessel's gyro and the Loran-C signal and computes the vessel's position and heading. This information is presented to the mariner in graphic as well as digital form. The graphic representation depicts the vessel with respect to channel bounds, aids to navigation, and other structures in the waterway depending on the scale used for the display. The digital display provides navigation information, such as speed, course, time to next waypoint, and cross track position relative to a trackline.

The system is accurate to within a twenty foot distance depending on local conditions. While other systems differ with respect to the display format used, e.g., graphic or digital, and the specific information presented to the mariner, they are similar with respect to the general positioning information provided, i.e., position relative to channel boundaries or centerline and position relative to waypoints.

There has been very little systematic research addressing the questions regarding the effects of precision electronic navigation aids on vessel pilotage. This has been partly due to their experimental nature and the efforts directed toward developing the technology needed to make the systems accurate and reliable. The research that has been conducted can be divided into field and simulator evaluations.

The field tests performed to date have been mainly directed toward the reliability of the aids and their acceptance by mariners using them. While user acceptance is an important element to actual usage of the aids, it does not directly demonstrate their effectiveness, i.e., that pilots will handle their vessels any better with the systems than without them.

Olsen et al. (1980) reported a field test of the PILOT aid aboard the USCG Cutter KATMAI BAY, an icebreaker in the St. Mary's River, during the winter of 1979-1980. While no quantitative evaluation was made, it was reported that PILOT was found to be "useful in thick fog and for starting turns based upon the distance to go". The aid was also easily mastered and well accepted by the ship's bridge crew. Similar findings were reported by Anthony and Sedlock (1981) for a field testing of the PILOT aboard three Great Lakes ore carriers. The vessels were from 700 to 1,000 feet in length with beams of up to 105 feet. In sections of the waterway they were transiting, channel widths were as little as 300 feet, so precision navigation was important. Following a three month evaluation period, a comprehensive questionnaire was used to collect data on PILOT's performance. The results indicated that the system was used and judged to be generally accurate and reliable. When asked if the mariners would use PILOT "blind", that is, in conjunction with radar, a majority claimed they would, but with reservations. While the nature of these reservations was not elaborated, the indication that these mariners would navigate by the system was a strong indication of user acceptance.

There have been several simulator experiments on the effectiveness of advanced navigation displays on ship-handling performance. Since some of the advanced navigation systems investigated were very similar to the types of precision electronic navigation aids of interest in the present study, the findings of those investigations will be discussed here.

Hayes and Wald (1980) utilized the Computer Aided Operations Research Facility (CAORF) to compare the effects of these systems on collision and grounding avoidance. The systems were (1) a conventional 16 inch radar, (2) a collision avoidance system (CAS) utilizing a predicted area of danger display, and (3) a collision avoidance system with a navigation option (CAS + NAV). The CAS + NAV provided a predicted area of danger format superimposed on a display providing exact ownship position information. Position information was in graphic "chart-like" form with shoal lines, channel boundaries, and navigation aids integrated with the CAS presentation. As such, the system is similar to the precision navigation system with the exceptions that (1) CAS information was provided and (2) digital positioning data was not provided.

Ship masters utilizing these aids experienced a variety of collision avoidance scenarios in which heavy fog limited visibility to .5 nm. The results indicated that the CAS + NAV group was superior in several areas of collision avoidance. The authors concluded that the masters were able to execute greater maneuvering of ownship, positioning the vessel closer to channel bounds and thereby increasing distance from other vessels, since they had knowledge of their location with respect to channel bounds. As a result, their performance was more effective than that of masters using the other two systems.

Increased vessel maneuvering with a CAS + NAV display, in comparison with a CAS, radar with RACONS, and traditional radar display was observed in another study (Cook, Marino, and Cooper, 1981). In this simulator investigation, vessel crews made low visibility approaches to a deepwater port complex (the Louisiana Offshore Oil Port) aboard a VLCC. The crews consisted of experienced VLCC masters and mates. Po.. experiment debriefing revealed that a majority of the masters preferred the CAS + NAV system to any of the others. These masters noted that they preferred that display because the information "could easily be transferred between the display and the chart".

A third investigation, which was conducted at CAORF (Cooper, Bertsche, and McCue, 1981), compared mariners' shiphandling performance using traditional radar and two different advanced bridge displays: CAS + NAV and Predictor Steering + NAV (predicted steering was projection of vessel's track along with CAS information). In all three systems a graphic display mode was used. The mariners were pilots who were familiar with the geographic areas studied and masters who were unfamiliar with those areas. The mariners conned a vessel through a variety of restricted waters scenarios under conditions of clear visibility, .5 nm visibility, and 300 yard visibility. Overall, trackkeeping performance was superior when using the advanced displays when compared with the radar in limited visibility conditions. In clear visibility, the performance of masters unfamiliar with the waterways was superior to their performance when using radar alone. The authors concluded that "the greatest benefit to those who used the advanced bridge display came from the presentation of channel boundaries and ownship's position relative to them" (p. ix).

A digital information format was compared with three different graphic presentations of precision navigation information in a simulation study by Bertsche, Cooper, Feldman and Schroeder (1980). The digital display provided data pertaining to crosstrack distance and direction, crosstrack speed and direction, distance to waypoint, rate of turn, course error and direction, recommended heading to steer, and recommended rate of turn. The graphic displays included (1) a "perspective" display representing what the pilot would see looking from the center of the bridge with channel boundary lines included, (2) a "steering" display showing a bird's eye perspective of ownship with channel boundary and a projected trackline showing ownship's drift angle (attitude) at the end of the line, and (3) a "graphic" display consisting of a bird's eye perspective of ownship with channel boundaries and a course vector. These aids were given to pilots who were asked to keep a vessel on a narrow channel's centerline. Strong winds occurred at times during the scenario. The results indicated that the digital and "perspective" displays resulted in inferior trackkeeping performance when compared with the other two displays. Both the "graphic" and "steering" displays resulted in superior pilotage performance.

Based upon these studies, some tentative conclusions regarding the effectiveness of displays providing precision navigation information may be formulated.

- Precision navigation information resulted in superior pilotage performance when limited visibility or strong winds existed.
- Precision navigation information permitted increased vessel maneuvering in a collision avoidance situation, presumably due to pilots' increased knowledge of the vessel's position with respect to fixed structures such as channel boundaries.
- Precision navigation information in graphic form was preferred to digital presentations. While this may have been a function of a need for increased training and familiarity with digital displays, graphic displays are generally associated with more rapid information processing since the display represents an integration of information in analog form.

- Precision navigation systems generally have been accepted by mariners who have been exposed to them in the field and in simulator studies.

While these studies provide important data with respect to the effectiveness and acceptability of precision electronic navigation systems, their results are limited in scope. Additional research is needed to undertake more comprehensive testing. Generally, these studies have been conducted under mildly adverse but not severe conditions. A rigorous test of the effectiveness of a precision navigation aid would occur when the mariner is put in a position of being required to execute precision shiphandling maneuvers with limited time to make decisions under extremely adverse conditions where most of the traditional positioning information is lost, i.e., aids to navigation, radar, etc.

It is this type of situation which can jeopardize the Sunshine Skyway Bridge in Tampa Bay. Tampa Bay is well known as an area of extreme thunderstorm conditions where a mariner can be deprived of almost all information regarding his position (limited visibility and rain cluttered radar presentation) while at the same time having his vessel subjected to extreme perturbing forces from intense and variable winds. While pilots would make every effort to avoid such conditions in the vicinity of the bridge, the sporadic nature of intense thunderstorms makes it possible to encounter them in the bridge area. Even if such an encounter may occur infrequently, the consequences can be great and tragic as the SUMMIT VENTURE incident demonstrated.

A precision electronic navigation aid may represent a solution to the problem of making a transit under the bridge during an unanticipated but extremely intense thunderstorm.
Such a recommendation was made by the National Transportation Safety Board (1981) following their investigation of the accident. Consequently, in 1982 the Florida House of Representatives passed a bill (No. 772) requiring the use of a precision navigation aid for vessels passing through Florida bridges.

One of the major purposes of this study is to evaluate the effects on shiphandling and, consequently, bridge safety of precision navigation systems when employed under extremely adverse environmental conditions.

2.3 MITIGATION OF RISKS TO THE NEW SUNSHINE SKYWAY BRIDGE

Following the collision between the SUMMIT VENTURE and the Sunshine Skyway Bridge in 1980, work began on the design of the replacement bridge. As discussed previously, one effort to minimize a future vessel-bridge incident was the decision to position the replacement bridge approximately 1,000 feet further away from the turn from Mullet Key to Cut A Channel and to increase its horizontal and vertical clearances for vessel passage. In addition, an elaborate pier protection system is planned. This solution can be classified within the channel-bridge geometry category.

A second strategy from this category aimed at minimizing the potential of future vessel-bridge interactions was to displace the turn required of the inbound mariner from .7 nm before the bridge to over 2.7 nm away. The plan includes the extension of Cut A channel approximately 2 nm seaward and the elimination of Mullet Key Channel as a main navigation channel. The extended Cut A channel would be joined with an extended Egmont Channel. The inbound mariner would then have a great amount of time between the turn and the bridge to assess and adjust for perturbing forces acting on the vessel. However, by moving the turn a 35 degree turn is created where previously there was only an 18 degree turn.

A third strategy to mitigate risks to the replacement bridge is the implementation of a precision electronic navigation aid system in the vicinity of the bridge. The system would be similar to those described in the previous section.

The purpose of the study to be described in this report was to examine the relative operational safety afforded the replacement of the Sunshine Skyway Bridge by the three mitigation strategies described above, i.e., the movement and redesign of clearances for the new bridge, the extended Cut A Channel, and the precision electronic navigation aid.

The safety of vessel transits through a bridge must be considered within the context of the entire system design of which the bridge is a part. Hence the interaction of many factors must be examined including:

- Bridge Design
- Channel Geometry
- Design Vessel Hydrodynamics and Aerodynamics
- Formal Aids to Navigation, Such as Ranges and Buoys
- Informal Navigation Aids, Such as Land Structures

- *Prevailing Current and Wind Forces*
- Visibility, Ambient Lighting, and Other Environmental Effects
- Human Operator Control and Decision Processes

Real-time, full-mission shiphandling simulation provides a research tool with which the complex interactions of these factors can be examined. The Maritime Administration's Computer Aided Operations Research Facility (CAORF) contains one of the world's most sophisticated shiphandling simulators and, as such, affords the opportunity to examine the relative value of alternative mitigation efforts prior to implementation.

The study examined the relative safety of the three mitigation strategies and compared them with the system design as it existed circa 1980. To accomplish this evaluation, four complete navigation system designs were compared:

- Navigational System Design 1 – The original Sunshine Skyway Bridge, in its original position, with the channel alignment and navigational aids as they existed in May 1980 when the SUMMIT VENTURE incident occurred. This system served as a baseline condition.
- *Navigational System Design 2 – The new Sunshine* Skyway Bridge with the currently existing channel alignment and recently improved navigational aids. *This system incorporated the new bridge design and* placement.
- *Navigational System Design 3 – The new Sunshine* Skyway Bridge with the currently existing channel alignment and recently improved navigational aids. In addition, a precision electronic navigation aid was included.
- Navigational System Design 4 – The new Sunshine Skyway Bridge with a new channel alignment consisting of the extension of Cut A Channel and a system of floating aids consistent with the markings of other channels and bends in Tampa Bay.

An additional factor that must be considered in relation to the safety of the new Sunshine Skyway Bridge is the environment. Weather in the Tampa Bay area can have a serious impact on bridge safety. Winds vary considerably throughout the year with an average speed of about 8 knots. Hurricane force winds occur periodically and sustained speeds of 50 knots are possible. High winds are most often out of the southwest or the north and can shift markedly, especially during heavy thunderstorms. Weather was implicated as a contributing factor in the SUMMIT VENTURE accident.

Visibility is frequently reduced by thunderstorms during summer months, which sometimes occur daily over a month's time. Heavy rain during such storms can, of course, significantly degrade a radar presentation due to clutter. During the winter months, evening fog becomes heavy about four days a month, reducing visibility well below 1 nm.

Due to the important influence of weather on bridge safety in Tampa Bay, this study concentrated on the relative differences between navigational system designs in adverse weather conditions when bridge safety would most probably be jeopardized.

CHAPTER 3

OBJECTIVES

The investigation described in this report was designed to provide data relating to the following questions:

1. Which of the four navigational system designs provided the safest passage under the Sunshine Skyway Bridge? They were:

- Navigational System Design 1 – The original Sunshine Skyway Bridge in its original position, with the channel alignment and navigational aids as they existed in May of 1980 when the SUMMIT VENTURE incident occurred.

- Navigational System Design 2 – The new Sunshine Skyway Bridge with the currently existing channel alignment and recently improved navigational aids.

- Navigational System Design 3 – The new Sunshine Skyway Bridge with the currently existing channel alignment and recently improved navigational aids. In addition, a precision electronic navigation aid was included.

- Navigational System Design 4 – The new Sunshine Skyway Bridge with a new channel alignment consisting of the extension of Cut A Channel and a system of floating aids consistent with the markings of other channels and bends in Tampa Bay.

Several corollaries to this major question were addressed:

a) What were the relative merits of the new bridge position as compared with the original bridge position? This question was indirectly addressed since there were differences between the navigational systems other than bridge position.

b) What were the relative merits of using the extended Cut A Channel design as compared with the present channel design?

c) What were the relative merits of a precision electronic navigation aid?

2. What was the effect of different forms of adverse conditions on the safety of bridge passage under each of the four navigational systems? Two different types of adverse environmental conditions were examined. The first was a heavy fog condition where eye visibility was reduced to near zero but where the radar presentation was unaffected. The second was an intense thunderstorm condition with heavy rain and high winds where eye visibility was impaired to a lesser degree than in heavy fog, but the radar presentation was impaired due to rain clutter. While safety under adverse conditions was of primary interest, a small number of experimental passages examined bridge transits under favorable conditions for reasons discussed in the next section.

3. Were there any interactions between navigational system designs and environmental conditions? For example, were some navigational system designs more affected by differing environmental conditions than others?

CHAPTER 4

EXPERIMENTAL METHODOLOGY

4.1 OVERVIEW

The simulation experiment will be described in this section. A brief overview of the study will be presented here and the specific details are elaborated in the following sections.

Each of seven Tampa Bay pilots conned a light 165,000 DWT tanker inbound from points approximately two to three miles seaward of the Sunshine Bridge to a point just beyond the bridge. The two independent variables examined were Navigational System Design and Environmental Condition combined to form nine experimental scenarios. Each pilot made two familiarization passages and nine experimental passages with each trip corresponding to one combination of Navigation System Design and Environmental Condition. A mate and helmsman were present on the bridge for each passage to assist the pilot and make the simulation more realistic with respect to bridge personnel requirements for vessel transits in restricted waterways during adverse weather. A bow lookout was also present during periods of limited visibility.

Performance measures were collected for each passage and came from three categories of dependent variables: vessels' proximity to bridge measures, vessel controllability measures, and pilots' subjective ratings.

4.2 STUDY COMPONENTS

4.2.1 Participants

The participants in this study were seven pilots from the Tampa Bay Pilots Association.

4.2.2 Data Base Specifications

Three separate simulation models of Tampa Bay were developed in order to simulate the four navigational system designs under investigation. In this section, the specifics of each model will be described preceded by an overview of the general data base requirements of each model.

4.2.2.1 General Data Base Requirements

Each model of Tampa Bay required the construction of five data bases: visual, radar, situation display, plotting, and depth/current/bank (DCB) data bases. These data bases were constructed from information collected from several sources including: NOAA Navigational Charts, U.S. Army Corps of Engineer Survey Maps, photographs of the Bay area in the vicinity of the Sunshine Skyway Bridge, photographs of the Florida Department of Transportation's model of the new bridge, Griener Engineering Sciences, Inc. drawings of the new bridge and its pier protection systems, United States Coast Guard data pertaining to aids to navigation, the **Coastal Pilot**, and discussions with the Tampa Bay Pilots and FDOT.

The data bases were integrated to yield an accurate unified representation of each model of Tampa Bay.

The visual data bases depicted the bow of ownship in Tampa Bay. The models consisted of water and landmasses extending from the sea buoy to the northern end of Tampa Bay. All aids to navigation, such as buoys and ranges, were positioned in their exact locations. Two versions of the bridge were developed, one representing the complete twin bridge span which existed prior to the SUMMIT VENTURE incident and the other the new cable-stayed structure under construction. Other informal aids such as lighthouses, buildings, etc., were included in the visual data bases to elicit realistic pilot shiphandling performance. In addition to water, land, and aids to navigation, other structures were included in the data base which were distinctive and/or aided pilots in recognizing the models as Tampa Bay.

The pilots' perspective of the visual scene was consistent with their height of eye aboard ownship's bridge and the vessel's direction of transit and position. How much of the visual scene was visible from the ownship did depend on the specific scenario requirements for visibility, which ranges from 0.1 nm (in thunderstorm and fog conditions) to nearly unlimited (in favorable weather conditions).

The radar data bases were developed in conjunction with the visual data base. Structures present in the visual data bases (although of course not necessarily visible from the ownship bridge) were represented in the radar data bases, e.g., buoys, bridge, landmasses, land structures, etc. The radar presentations on the CAORF bridge are made via actual radar in realistic planned position indicator (PPI) format including shadow, fading, and clutter effects.

The depth/current/bank data bases modelled the existing and proposed (extended Cut A Channel) channel designs. Bank forces were calculated by an on-line program which determines appropriate bank effects on the basis of the following parameters:

- Bank heights
- Water depth
- Vessel draft
- Vessel heading
- Vessel speed
- Distance between vessel and bank wall.

The situation display and plotting data bases represented aerial perspective of channels, aids to navigation, landmasses, and important structures present in the models of Tampa Bay. The situation display data base was used to monitor vessel transits while on-line. The plotting data base was used to produce track plots following completed vessel transits.

4.2.2.2 Tampa Bay May 1980 Model

This data base was generally described in NOAA Chart 11414 - 25th Ed. However, several changes to that chart were made in order to accurately depict the Bay at the time of the SUMMIT VENTURE incident. A U.S. Army Corps of Engineers (USACE) channel widening and deepening project was underway at the time and work around the bridge had been completed before the accident although the work was not shown on the chart. The changes made for the purposes of this study are outlined as follows:

A. Mullet Key Channel was dredged to 600 feet wide and 43 feet deep.

B. Cut A Channel was dredged to 500 feet wide and 43 feet deep.

Even though these channels were widened, buoys remained in the charted positions. (They will be moved when the USACE project is completed). The resulting model of Tampa Bay is depicted in Figure 2.

4.2.2.3 Tampa Bay Existing Channel - New Bridge Model

This data base was generally described in NOAA Chart 11414 - 27th Ed. However, many changes to the charted information were required. These changes are listed below in three categories: Bridge, Channel, Aids to Navigation.

A. Bridge Changes

This data base included the new Sunshine Skyway Bridge. The existing bridge was not included. The bridge was positioned about 1,000 feet east of the existing bridge at the center of Cut A Channel. Appendix B presents figures describing the new bridge's position, appearance, and pier protection design.

The bridge markings included a green light to mark the center of the channel and amber lights to mark channel boundaries.

B. Channel Changes

1. Mullet Key Channel was modelled at 600 feet wide and 43 feet deep.

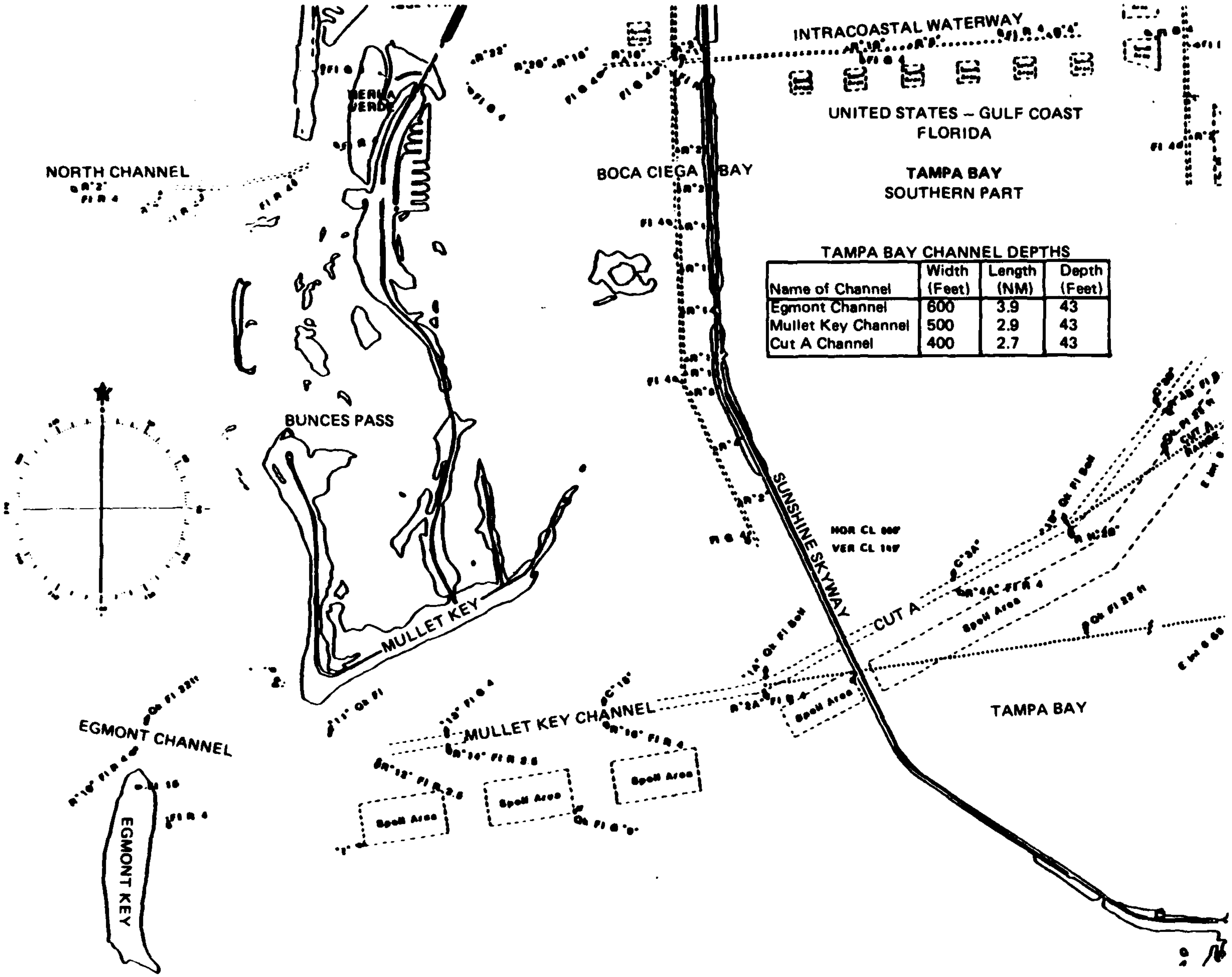
2. Cut A Channel was modelled at 500 feet wide and 43 feet deep.

C. Aids to Navigation

Changes made to buoy configurations in the channels of Tampa Bay are listed below. The stated positions represent Coast Guard identified current positions which are for charted, not actual, channel boundaries. The data base modelled buoys on actual boundaries, as will be the case when the current dredging project is completed. Hence, buoys were moved from their listed positions (about 50 feet in most cases) for the purposes of this study.

1. Buoy "10" in the widener from Cut C to Cut B Channels was moved to the center of the widener:
   L 27° 41' 40.1"N / λ 82° 33' 28.6"W.

2. Buoy "8B" in the Cut B Channel was moved to the northern corner of the widener intersect with Port Manatee Channel:
   L 27° 39' 43.6"N / λ 82° 35' 58.4"W.



TAMPA BAY CHANNEL DEPTHS

Name of Channel	Width (Feet)	Length (NM)	Depth (Feet)
Egmont Channel	600	3.9	43
Mullet Key Channel	500	2.9	43
Cut A Channel	400	2.7	43

Figure 2. The 1980 Sunshine Skyway Bridge and Channel Design

3. Buoy "1A" was moved to the eastern corner of the widener joining Cut A and Mullet Key Channels: L 27° 36' 56.8" N/λ 82° 40' 01.4"W, and changed to F1. G. 2.5 sec. - bell removed.

4. New Buoy "25" was added to the western corner of the widener joining Cut A and Mullet Key Channels: L 27° 36' 48.0"N/λ 82° 40' 21.0"W and is Qk.F1. G.

5. Buoy "C15" was replaced with buoy "23" at same location: L 27° 36' 38.2"N/λ 82° 41' 43.3"W, and is F1. G. 4 sec.

6. Bouy "R16" was renamed "R24" and moved: L 27° 36' 31.3" N/λ 82° 41' 42.1"W.

7. Buoy "13" was renamed "21" and moved: L 27° 36' 27.2" N/λ 82° 43' 00.1" W.

8. Buoy "R14" was renamed "R22" and moved: L 27° 36' 20.4" N/λ 82° 42' 58.9"W.

9. Buoy "11" was renamed "19" and moved: L 27° 36' 19" N/λ 82° 44' 17"W.

10. Buoy "R12" was replaced with buoy "R20" and moved: L 27° 36' 09" N/λ 82° 44' 20"W, and is F1.R. 2.5 sec. with bell.

11. Buoy "17" was added to location: L 27° 36' 33" N/λ 82° 45' 28" W, and is F1.G. .6 sec.

12. Buoy "18" was added to location: L 27° 36' 23" N/λ 82° 45' 31"W, and is F1.R. 6 sec.

13. Buoy "C9" was eliminated

14. Buoy "R10" was eliminated

15. Buoy "15" was added to location: L 27° 36' 47" N/λ 82° 46' 40" W, and is F1.G. 4 sec.

16. Buoy "16" was added to location: L 27° 36' 37.3" N/λ 82° 46' 59.2"W, and is Qk.F1 R. with bell.

17. Buoy "R8" was eliminated.

18. Buoy "13" was added to location: L 27° 36' 34" N/λ 82° 48' 43" W, and is F1.G. 2.5 sec. with a whistle.

19. Buoy "R14" was added to location: L 27° 36' 26" N/λ 82° 48' 42"W, and is F1.R. 2.5 sec.

20. Buoy "C5" was eliminated.

21. Buoy "R6" was eliminated.

22. Buoy "11" was added to location: L 27° 36' 24" N/λ 82° 50' 26"W, and is F1.G. 6 sec.

23. Buoy "R12" was added to location: L 27° 36' 16" N/λ 82° 50' 25"W, and is F1.R. 6 sec.

24. Buoy "3" was eliminated.

25. Buoy "N4" was eliminated.

26. Buoy "1" was renamed "9" and moved to: L 27° 36' 14" N/λ 82° 52' 09"W.

27. Buoy "R2" was renamed "R10" and moved to: L 27° 36' 07" N/λ 82° 52' 14" W, and the bell eliminated.

28. Buoy "7" was added to location: L 27° 36' 02" N/λ 82° 54' 13"W, and is F1.G. 2.5 sec.

29. Bouy "R8" was added to location: L 27° 35' 53" N/λ 82° 54' 12"W, and is F1.R. 2.5 sec. with a bell.

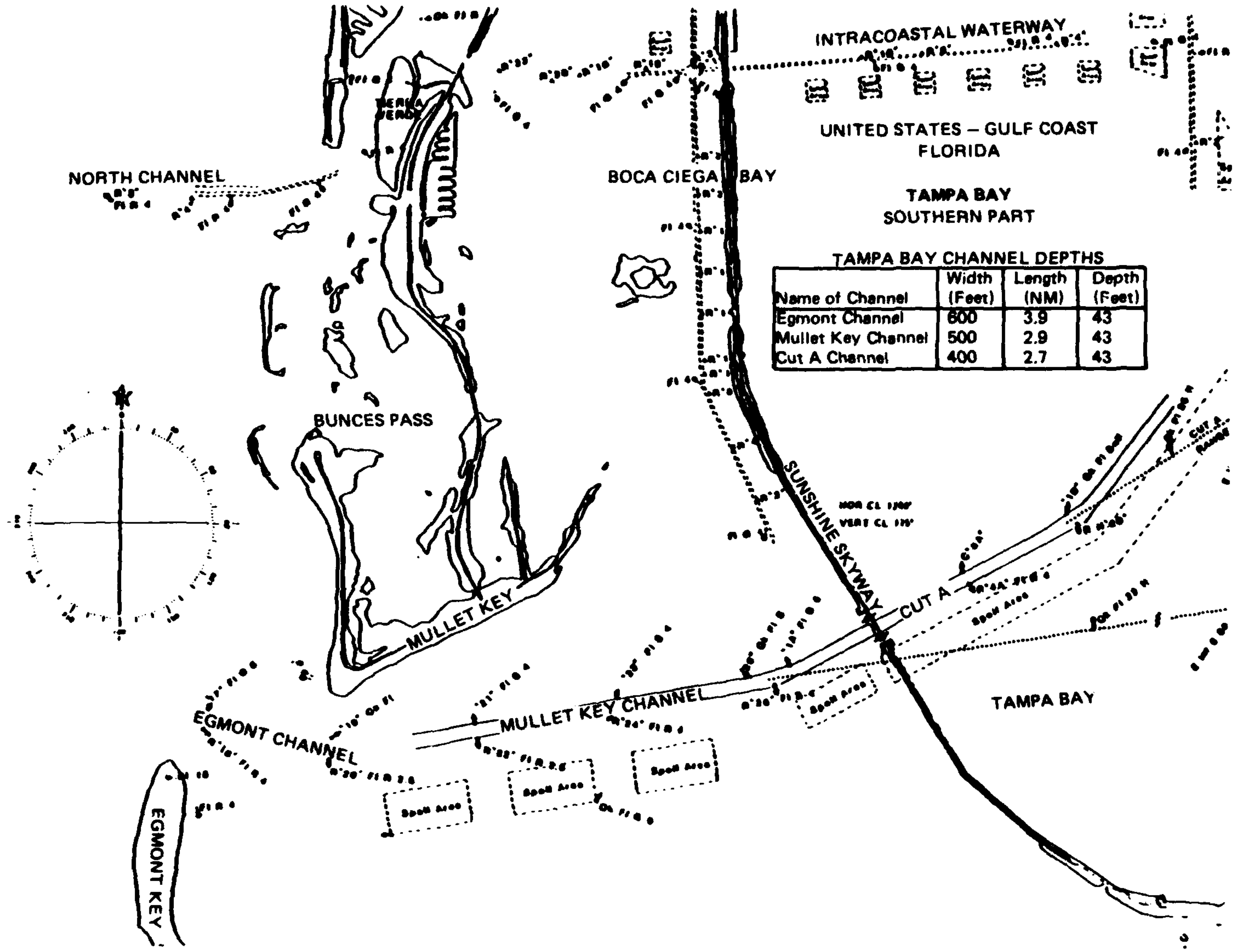
30. Buoy "BW" was eliminated.

31. Buoy "5" was added to location: L 27° 35' 53" N/λ 82° 55' 34"W, and is F1.G. 6 sec. with a whistle.

32. Buoy "R6" was added to location: L 27° 35" 45" N/λ 82° 55' 33" W, and is F1.R. 6 sec.

33. Buoy "5" was renamed "3" and moved: L 27° 36' 24" N/λ 82° 50' 26"W.

The bridge area for this data base is presented in Figure 3.



TAMPA BAY CHANNEL DEPTHS

Name of Channel	Width (Feet)	Length (NM)	Depth (Feet)
Egmont Channel	600	3.9	43
Mullet Key Channel	500	2.9	43
Cut A Channel	400	2.7	43

Figure 3. The Replacement Sunshine Skyway Bridge and Currently Existing Channel Design

4.2.2.4 Tampa Bay Extended Cut A Channel Model

This data base was generally described in NOAA Chart 11414 - 27th Ed. Major changes of charted information were required. However, there was no specific design plan for this data base, e.g., no formal Army Corps of Engineers or U.S. Coast Guard design. The design, therefore, was constructed by CAORF staff to include the following elements:

A. Cut A Channel was extended seaward for a distance of 2 nm.

B. Egmont Channel was extended to intersect with the extended Cut A Channel.

C. Mullet Key Channel was eliminated.

D. The new Sunshine Skyway Bridge described in Section 4.1.2.3 replaced the charted Sunshine Skyway Bridge.

E. Aids to Navigation in the channels from the Bridge position into the Bay were the same as described in Section 4.1.2.2.

Aids to navigation in the new channel section were made consistent with the markings of other channels in Tampa Bay and are shown in Figure 4.

4.2.3 Ownship Model

Two considerations went into determining the best vessel model to be used in this study. First, the vessel modelled should be at least as large as the largest ship currently calling on Tampa Bay since in general a large vessel poses a greater safety risk than a small vessel. The largest vessels to have used the port thus far are in the 112,000 to 126,000 DWT class. (Greiner Engineering Sciences Inc., 1982). It was considered desirable to use a slightly larger vessel in anticipation of potentially larger vessels which can be expected in the future when the current channel widening and deepening project is completed. The second consideration was that the vessel should be responsive to wind effects since strong and variable winds pose safety risks for vessels in Tampa Bay.

The vessel chosen to meet these considerations was a light (unloaded) 165,000 DWT tanker. The tanker was modelled to be approximately 951 feet long, 155 feet wide, with a light draft of 28 feet. This tanker is slightly larger than the largest ship currently passing under the Sunshine Skyway Bridge. This insured that the results of the study include an adequate margin of safety for smaller ships currently using the port and large ships which Tampa Bay may see in the near future.

Since the vessel was modelled as unloaded, it was much more influenced by wind due to its greater sail area (freeboard) compared with a loaded tanker. An additional consideration was that most of the collisions between ships and the Sunshine Skyway Bridge have involved light vessels, e.g., the M/V SUMMIT VENTURE.

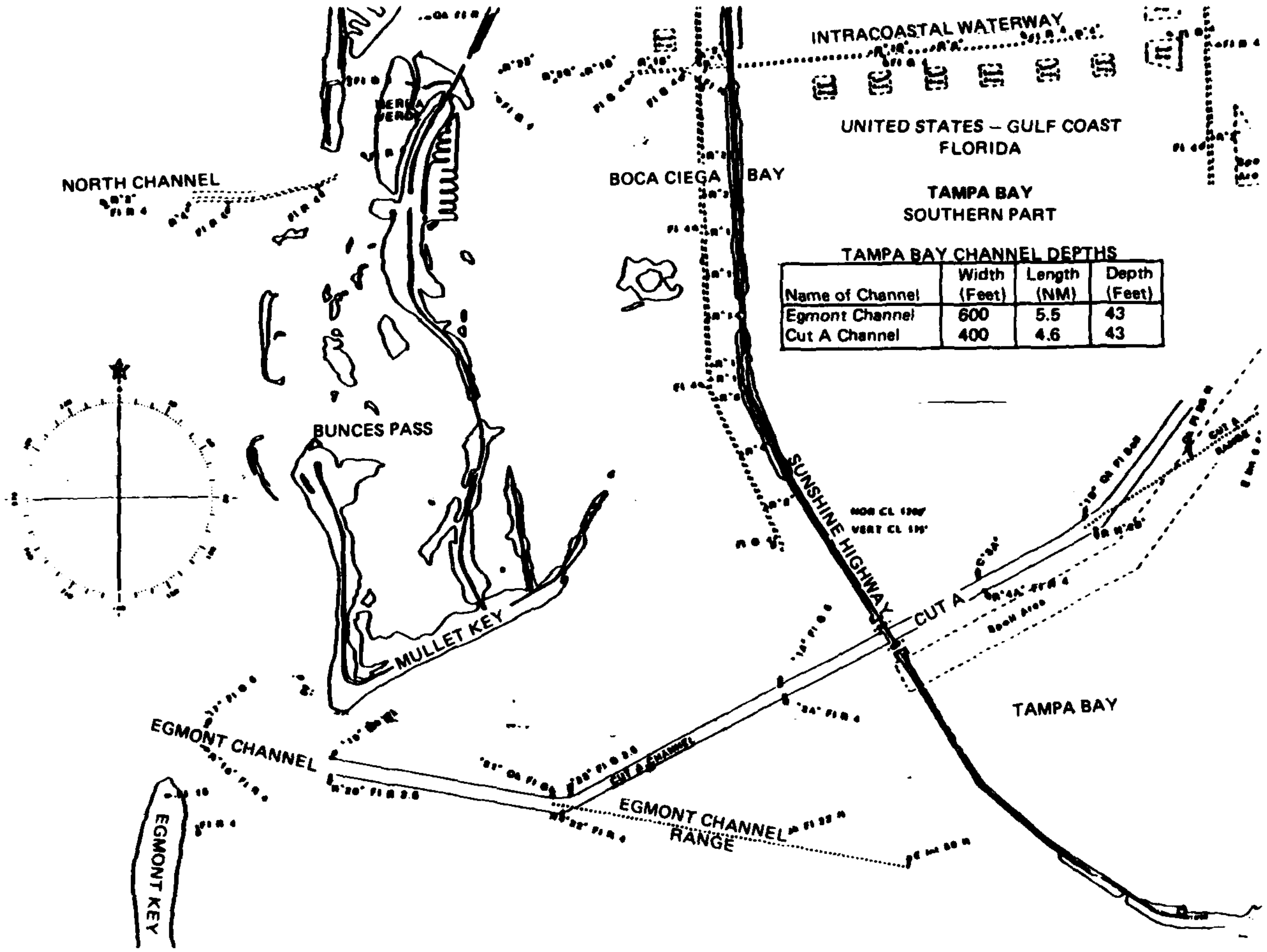
A general description of the vessel and its maneuvering characteristics are presented in Figure 5.

4.2.4 Ownship Bridge Equipment

The bridge of ownship was equipped with standard instrumentation composed of actual marine hardware like that found aboard large merchant vessels (see Table 3). In addition to standard equipment, a Precision Electronic Navigation Aid (PENA) was made available for certain passages. The PENA was modelled to represent a generic precision positioning system providing both analog and digital information. The specific source of position information, e.g., LORAN signal, cable, etc., was not of concern in this study. Therefore, when available the PENA functioned properly and was not influenced by thunderstorm activity, bridge structures, or any other factors that might influence any one specific system.

Figure 6 illustrates a typical PENA display. The analog portion of the display provided a graphic representation of the vessel's position consisting of an outline of the vessel with respect to channel boundaries, aids to navigation, and bridge structures. A six minute vector representing ownship's projected "course made good" was also displayed. This information was presented on the ship's bridge via a CRT display. The display provided a two nm scale with ownship positioned in the left third of the screen; the other two thirds represented the area into which ownship was sailing (see Figure 6). Information going to the analog display was updated approximately once every second.

The digital display contained similar information in numerical rather than graphic form. Of critical importance to precision navigation was distance to next turn point, distance off track (the channel centerline), speed along track, speed across track, crab angle, and rate of turn (see Figure 6). This information was presented on the ship's bridge via a second CRT display positioned alongside

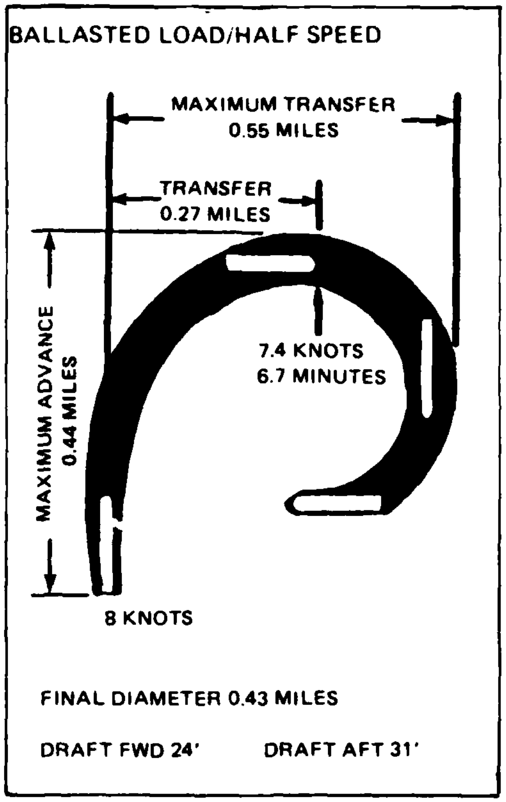


TAMPA BAY CHANNEL DEPTHS

Name of Channel	Width (Feet)	Length (NM)	Depth (Feet)
Egmont Channel	600	5.5	43
Cut A Channel	400	4.6	43

Figure 4. The Replacement Sunshine Skyway Bridge and Extended Cut A Channel Design

TURNING CIRCLE DIAGRAM



Length	951'
Beam	155.4'
Draft	27.9'
Capacity	165,000 DWT

Maximum Rudder Angle	STARBOARD RIGHT 40°	PORT LEFT 40°

TIME AND DISTANCE CRASH STOP

Engine Order	Full Lead Time (Min.)	Full Lead Distance Miles
Full Sea Speed	11.7	1.22
Full Ahead	5.6	0.61
Half Ahead	5.0	0.35
Slow Ahead	3.9	0.11

ENGINE ORDER/R.P.M./SPEED

Engine Order	RPM	Speed (Knots) Full Load
Full Sea Speed	95	17.4
Full Ahead	60	9.3
Half Ahead	40	5.6
Slow Ahead	20	4.2
Dead Slow Ahead	10	1.1
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	33	
Full Astern	50	Time Full Ahead RPM to Full Astern 67 Seconds

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather—10 knots or less, calm sea.
2. No current
3. Water depth 3 times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less advance.
2. There is no appreciable difference in the time or distance of ADVANCE or TRANSFER when making a turn to port or starbord. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation, the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

Figure 5. Ballasted 165.000 DWT Tanker Description and Deep Water Maneuvering Characteristics Information

TABLE 3. OWNSHIP BRIDGE EQUIPMENT

• Steering stand with gyro repeater, rate of turn indicator
• Overhead 3-face rudder angle indicator
• Bulkhead mounted gyro repeater
• Rate of turn indicator
• Engine order repeater
• RPM indicator (2)
• Engine order telegraph/throttle
• Speed log (through the water speed)
• Digital distance log
• Digital clock
• VHF radio-telephone
• Manual whistle control
• Automatic whistle timer control
• Sound powered phone
• Digital depth sounder
• Relative wind indicators (speed and direction)
• Bridge wing gyro repeater with pelorus mounted (2)
• 3 cm and 10 cm radars (with computerized plotting aid)
• Precision Electronic Navigation Aid (PENA) (available for certain passages only)

DIGITAL DISPLAY

OWNSHIP DATA	BRIDGE TIME: 12:03:30	
HDG: 77.50 DEG	COURSE: 89.00 DEG	SPEED: 10.05 KTS
LAT: 27D 36M 55	LONG: 82D 41M 18S	
NORTH:	EAST:	
NM TO TURN PT	0.20	
FEET OFF TRACK	15L	
KTS ALONG TRACK	9.45	
FPM CROSS TRACK	6R	
OWNSHIP CRAB ANGLE	-11.50	(in degrees)
OWNSHIP RATE OF TURN	- 0.0354972	(in degrees per second)
RPM #1	58.25	
RPM #2	0.00	

GRAPHIC DISPLAY

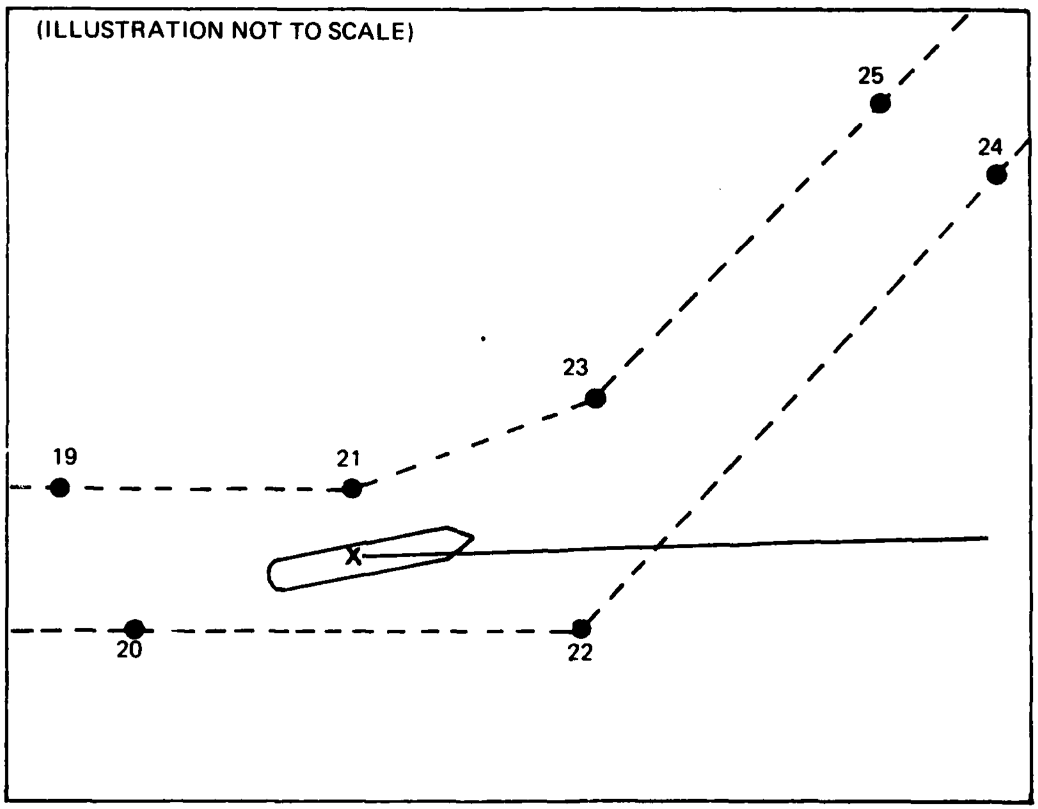


Figure 6. Bridge Display Provided by the Precision Electronic Navigation Aid

of the analog display monitor. It was updated approximately once every 18 seconds.

The degree of error incorporated into both systems was approximately 5 feet.

4.3 EXPERIMENTAL DESIGN

4.3.1 Independent Variables

Two independent variables were examined in this study. They were Navigational System Design and Environmental Condition.

Navigational System Design refers to a specific channel design, navigational aids configuration and Sunshine Skyway Bridge combination. This variable had four levels:

1. Navigational System Design 1 (NSD1) — The original Sunshine Skyway Bridge in its original position, with the channel alignment and navigational aids as they existed in May of 1980 when the SUMMIT VENTURE incident occurred. This design is illustrated in Figure 2.

2. Navigational System Design 2 (NSD2) — The new Sunshine Skyway Bridge with the currently existing channel alignment and recently improved navigational aids. This design is illustrated in Figure 3.

3. Navigational System Design 3 (NSD3) — The new Sunshine Skyway Bridge with the currently existing channel alignment and recently improved navigational aids (Figure 3). In addition, a Precision Electronic Navigation Aid (PENA) was included in this design.

4. Navigational System Design 4 (NSD4) — The new Sunshine Skyway Bridge with a new channel alignment consisting of the extension of Cut A Channel and a system of floating aids consistent with the markings of other channels and bends in Tampa Bay. This system is illustrated in Figure 4.

Environmental Conditions refers to a specific combination of current, wind, and visibility. This variable had three levels:

1. Favorable Condition

- Current-slack
- Wind-8 knots from 285°T± 45°
- Visibility - Clear 12 nm

2. Intense Thunderstorm Condition

- Current - 2 knots flood/fair current
- Wind - Mean of 40 knots with gust ± 10 knots from 330°T±45°
- Visibility - restricted to approximately 0.1 nautical mile due to heavy rain which also produced a high degree of rain clutter in the radar presentation

3. Heavy Fog Condition

- Current - 2 knots flood/fair current
- Wind - 8 knots from 285°T±45°
- Visibility - restricted to approximately 0.1 nautical mile with no effect on radar

4.3.2 Dependent Variables

A thorough examination of the safety of bridge passage required the collection of dependent variables (performance measures) from three categories. The first and most important represented the vessel's proximity to bridge structures. The second represented the vessel's controllability while making bridge passages. The third set represented pilots' subjective evaluations as to the safety of bridge transit. A list of the variables in each of these categories is presented in Table 4.

In an evaluation of bridge safety, the proximity of vessels to bridge structures is of course of primary concern. Three measures of proximity were examined and each was calculated from the point at which the bow reached any bridge structure to the point at which the stern cleared all bridge structures:

- Closest Point of Approach (CPA) of ship to bridge represented the single closest distance between any portion of the vessel and any portion of the bridge, including its protective structures. The measure was, therefore, an indication of extreme values and not overall proximity of the vessels to bridge structures. With respect to bridge safety, however, it was a measure of extreme importance since a value of zero indicated contact between vessel and bridge.

- Average Distance of Ship to Bridge represented the mean of all values of distance of vessel from bridge calculated while any portion of the vessel was passing bridge structures. It gave an overall indication of how close vessels were getting to bridge structures.

TABLE 4. DEPENDENT VARIABLES RELATING TO THE SAFETY OF SUNSHINE SKYWAY BRIDGE PASSAGE

Proximity Measures

- Closest Point of Approach (CPA) of ship to bridge
- Average distance of ship from bridge
- Variability of ship's distance from bridge

Vessel Controllability Measures

Yawing Characteristics

- Variability of heading
- Average absolute rate of turn (yaw rate)
- Variability of rate of turn

Swept Path

- Average "swept path" during bridge passage
- Variability of "swept path"

Deviation from Channel Centerline

- Average absolute deviation of ship's track from channel centerline
- Variability of ship's track from channel centerline

Rudder Activity

- Average absolute rudder angle
- Variability of rudder angle
- Number of rudder reversals

Pilot's Evaluation

Pilotage Evaluation Rating Scale

- Cognitive Load Scale Score
- Stress Scale Score
- Task Difficulty Scale Score
- Shiphandling Scale Score
- Pilot Workload Estimation Score
- Composite Workload Score

Pilot Opinion Questionnaire

- Various open-ended questions pertaining to the experimental conditions

- Variability of Ship's Distance from the Bridge provided an indication in units of standard deviation of the fluctuation of the vessel's distance from the bridge. Since this study examined one-way traffic situations, the safest performance would have been to maintain maximum distance from bridge structures and, therefore, low variability. Note, however, that this measure is insensitive to the distance of the vessel from the bridge, i.e., a vessel could have low variability in distance from the bridge but nevertheless be close to it.

Taken together, these three measures provide a complete picture of the proximity of vessel to the Sunshine Skyway Bridge. To minimize the chances of bridge contact, pilots would have wanted to maximize CPA and average distance from bridge structures while minimizing the standard deviation (variability) of these distances. Navigational system designs were considered safer than others to the extent that they were significantly closer to this ideal. Proximity variables were calculated from data collected by computer every 15 seconds.

While measures of proximity are of major importance, the effects of the various navigational system designs on how pilots control and manuever their vessels were of interest as well. However, it should be noted that an interpretation of these variables is not straightforward and cannot be made independently from vessel proximity information. This point will be elaborated before the specific dependent variables are presented.

What can be concluded from the finding that one navigational system design leads to greater pilot maneuvering of his vessel than another design? The answer to this question depends upon the differences between those designs in their tendency to enable the pilot to maximize his vessel's distance from bridge structures. If both designs result in equal pilot performance in maintaining distance from the bridge, then the design leading to less maneuvering would be preferred. That is, the design which enabled pilots to maximize vessel distance from the bridge with minimal maneuvering of the vessel would be considered a safer design. Such an interpretation of vessel controllability measures would **not** be made, however, if a difference had been observed between the two designs on proximity measures. If a design A was found to provide greater distance from bridge structures than design B, controllability measures would only indicate how the difference was achieved. The observation that design A was associated with greater vessel maneuvering would not lead to the conclusion it was less safe than design B. Instead, the greater maneuvering would be indicative of increased pilot control activity leading to greater vessel distance from bridge structures than the other design. (Note that differences in controllability measures can also result from differences in piloting styles but these differences were controlled in the present study since each pilot participated in each navigation system design condition).

The interpretation of controllability measures, therefore, is dependent upon the differences observed between navigational system designs on proximity variables. Holding proximity values constant (no differences between navigation system designs), less maneuvering of vessels is preferred. Given no differences between designs in terms of proximity from bridge measures, the design requiring fewer maneuvers by the ship to maintain its distance from the bridge would be considered safer. However, maneuvering is not preferred if it leads to **closer** proximity of the vessel to the bridge.

With this logic in mind, measures along four dimensions of controllability were calculated: yawing characteristics, swept path, deviation from channel centerline, and rudder activity. In each case higher values were indicative of a pilot's maneuvering of the vessel or a perturbing force acting on the vessel. The first dimension pertained to the vessel's yawing behavior, i.e., the vessel's oscillation along the Z axis while making a bridge passage. Three variables representing this yawing activity were calculated:

- Variability of Heading provided a measure, in units of standard deviations, of the degree of fluctuation in the vessel's heading.

- Average Rate of Turn or Yaw Rate represented the rate at which the vessel's heading was changing.

- Variability of Rate of Turn provided a measure of the changes in vessel's yaw rate in standard deviation units.

Measures of yaw alone were insensitive to the amount of deviation between the vessel's heading and course made good. Therefore, swept path measures were calculated. Swept path refers to the area of the water's surface swept by the hull of the vessel transiting the waterway. The minimum swept path width would equal the vessel's beam while the maximum would be approximately equal to the vessel's length when it was travelling nearly sideways, or perpendicular to its fore and aft centerline. A certain degree of swept path in excess of beam was necessary to adjust for environmental forces and to make turns.

In general, however, the greater the swept path, given equal proximity from bridge structures, the more diminished the vessel's response capacity. Two swept path variables were calculated:

- Average Swept Path provided an overall summary of a vessel's swept path during a bridge transit.
- Variability of Swept Path provided an indication of the fluctuation in a vessel's swept path during a bridge transit.

Swept path measures were, however, insensitive to the vessel's position within the channel, e.g., a vessel could have a low swept path but be out of the channel boundaries. Therefore, measures of the vessel's deviation from the channel centerline were obtained. Given the one-way traffic situation and the value of maximizing distance from bridge, the channel centerline was the optimal vessel location. Two measures of deviation from channel centerline were calculated and each was based upon the furthest distance of any portion of the vessel from the channel centerlines:

- Average Absolute Deviation from the Channel Centerline provided a measure of the vessel's deviation from its optimal path.
- Variability of Absolute Deviation from the Channel Centerline was an indication of the vessel's movement about the Channel Centerline in units of standard deviations.

Measures of yaw, swept path, and deviation from centerline were insensitive to the amount of control responses necessary to keep the vessel under control. Therefore, rudder angle measures were obtained. The greater the amount of rudder used to maneuver the vessel, the less was available as reserve capacity to execute additional maneuvers. Three measures of rudder angle behavior were calculated:

- Average Absolute Value of Rudder Angle provided a measure of the overall amount of rudder needed to maneuver the vessel.
- Variability of Rudder Angle Absolute Value provided a measure of the changing of rudder angle in standard deviations units.
- Number of Rudder Reversals provided an index of frequency with which the rudder was shifted across the midship position.

Controllability variables were calculated based upon data collected by computer every 15 seconds from a point .5 nm before the bridge until the scenario termination. All data, therefore, were collected after the turn into Cut A channel.

The final category of dependent variables pertained to the pilot's subjective evaluations of the experimental conditions under investigation. The logic behind the interpretations of these variables was much the same as the logic behind vessel controllability measures. With respect to bridge safety, these measures could not be interpreted apart from the results from the other variable categories. Generally, if no differences were found among navigation system designs on proximity and controllability variables, then designs which were associated with less stress and difficulty for the pilot would be considered safer. When the demands placed upon the shiphandler are excessive, the pilot would have little reserve decision making capacity to handle additional problems that might arise. Pilot subjective evaluations, like other variable categories, were not interpreted in absolute terms but in terms of relative differences among experimental designs. Data on these variables were collected by means of a rating scale called the Pilotage Evaluation Rating Scale (PERS) distributed to pilots after each individual passage and a Pilot Opinion Questionnaire given to pilots following all their passages.

The PERS was used to obtain pilots' evaluations of the relative demands of each experimental condition. A copy of the scale has been provided in Appendix C. Individual items were combined into scale scores yielding measures on the following variables:

- Cognitive Load Scale Score provided an index of the demands placed upon the pilots' information processing capabilities.
- Stress Scale Score was a measure of the degree of arousal or stress experienced by the pilot during each transit.
- Task Difficulty Scale Score represented the degree to which pilots experienced difficulty in making the transit.
- Shiphandling Scale Score provided the pilots' estimates on the difficulty encountered in controlling the vessel.
- Pilot Workload Estimation Score was a measure of the pilots' direct rating of workload.
- Composite Workload Score provided an overall evaluation of the workload assigned to that condition. It reflected a composite of all items.

The Pilot Opinion Questionnaire was used to obtain pilot opinion on various aspects of the simulation including the quality of the simulation, the usefulness of the Precision Electronic Navigation Aid, and the value of the extended Cut A Channel. A copy of this scale is contained in Appendix C.

4.3.3 Logic of the Experimental Design

The central focus of this investigation was to determine the relative safety for bridge passage of the four navigational system designs defined in Paragraph 4.2.1 Independent Variables, under a restricted set of environmental conditions.

An ideal study would have compared these systems on a wide range of conditions generated through a factorial combination of many levels of variables such as current, wind, visibility, time of day, traffic conditions, transit direction, vessel types, etc. The resulting experimental conditions would number in the hundreds and would have been prohibitively time consuming and expensive to investigate. The alternative strategy employed in this study was to compare the navigational system designs under a smaller set of reasonable "worst case" situations and estimate the relative safety of each. Such an approach, however, requires making certain assumptions regarding cases not examined. The logic of this approach and the nature of the assumptions it required are made explicit below.

Alternative Navigational System Designs 2, 3, and 4 were compared in an effort to identify the design which would provide for the safest transit of vessels under the new Sunshine Skyway Bridge. The evaluation of these alternative designs required the development of a yardstick against which the relative safety of each could be compared. Navigational Design 1, the 1980 channel approach – complete twin span bridge model, served this purpose. Under adverse conditions this design was considered least safe since the bridge was closer to the turn from Mullet Key to Cut A Channel and the bridge model provided for less horizontal clearance for vessel passage when compared with the alternative designs. Under favorable environmental conditions, Navigational System Design 1 was regarded as adequately safe since it was the design in effect for many years in Tampa Bay and was considered problematic under adverse, not favorable, environmental conditions. The range in vessel behavior in Navigational System Design 1 under adverse and favorable conditions was, therefore, used as a yardstick from unsafe to adequately safe against which to compare the alternative designs. If any of the alternative designs produced performance under adverse conditions was worse than performance under Design 1 under the same conditions, then its safety would be suspect. Alternatively, if the alternative design were associated with performance superior to that of Design 1, then the relative degree of safety increment could be compared against Design 1 under favorable conditions.

The alternative designs were not examined under favorable conditions since performance under these conditions was assumed to be at least as safe as Design 1 because the new bridge was further from the turn into Cut A Channel and the bridge provided greater horizontal clearance. Thus, it was considered unlikely that the alternative designs would be less safe under favorable conditions than Design 1. Since Design 1 was considered adequately safe under favorable conditions, it was considered unnecessary to examine the alternative designs under those conditions. Furthermore, any specific violations of this assumption should have been detected in comparisons among the four navigational system designs under adverse conditions. That is, it seemed unlikely that an alternative design would be safer than Design 1 under unfavorable conditions yet less safe under favorable conditions.

As stated previously, a wide range of environmental conditions was possible. Since it was not feasible to investigate all possible conditions, a subset of three environmental conditions was investigated – one represented typical favorable environmental conditions and two represented different types of "typical" but extreme adverse conditions. Each condition represented a combination of environmental variables selected because they typified conditions in the Tampa Bay area. In heavy fog, eye visibility was reduced to near zero while the radar presentation was affected little. In an intense thunderstorm, both eye visibility and radar were affected. The radar presentation was severely impaired by rain clutter. The thunderstorm condition also subjected the vessel to the effects of high and variable winds. Since the adverse conditions were extreme, the assumption was made that the great majority of environmental conditions not examined would fall within the range presented in the study. Hence, the study would provide an adequate safety margin for all but highly infrequent extremely adverse conditions such as hurricanes.

The two independent variables, Navigational System Design (which had four levels) and Environmental Condition (which had three levels), could have been combined to form a total of 12 experimental conditions. However, since only Navigational System Design 1 was examined under favorable conditions, the study investigated a total of nine experimental conditions. These conditions are listed in Table 5. The scenarios developed to represent these experimental conditions are presented in the next section (Paragraph 4.4).

Each pilot who participated in the study was exposed to the entire set of experimental conditions. The experimental design used, therefore, was a Randomized Block Factorial (Kirk, 1968). The presentation of experimental conditions to each pilot was counterbalanced to avoid confounding practice and fatigue effects with experimental conditions.

4.4 SCENARIO DESIGN

The nine experimental conditions investigated in this study gave rise to nine scenarios. In addition, two scenarios were designed to provide simulator familiarization to the pilots. Each pilot, therefore, experienced a total of eleven scenarios. The scenarios were labeled from 1 through 9 corresponding to experimental conditions 1 through 9 and the familiarization scenarios were labeled A and B. In this section, the eleven scenarios will be described in general terms. The specific operating parameters of each scenario are presented in the Scenario Definitions contained in Appendix D.

For all scenarios, pilots had the assistance of a licensed mate and helmsman on the bridge. The mates were required to assist pilots in whatever way the pilots deemed necessary, in the same way as would occur on a merchant vessel. The helmsmen were required to execute pilots' rudder and course commands. In addition to the mate and helmsman, pilots had a "lookout" positioned at the bow during all scenarios where limited visibility would occur, i.e., thunderstorm and fog conditions. The lookout was actually a CAORF staff member who communicated with the pilot or the mate over the ship's sound powered phone. The function of the lookout was twofold. First, to spot aids to navigation or bridge structures when visibility was severely restricted. The lookout would call the bridge whenever any aid or bridge structure was within 0.1 nm (the prevailing visibility when limited) of the bow and report the object's approximate location with respect to the vessel, e.g., "a red buoy two points off the starboard bow". When the lookout was called from the bridge, his or her responses were always based on the visibility restrictions. The second role of the lookout was to report to the bridge an impending thunderstorm encounter. Since certain real world cues to a thunderstorm onset were absent from the simulation, e.g., seeing the thunderstorm approaching from a distance or tracking it on radar, a report from the lookout was used to alert the pilot to the storm's approach. Approximately one minute prior to the vessel's encounter with a thunderstorm, the lookout would call the bridge and report spotting some "intense thunderstorm activity" coming from the northeast and that the vessel would encounter the storm in about a minute or so.

TABLE 5. EXPERIMENTAL CONDITIONS RESULTING FROM THE COMBINATION OF INDEPENDENT VARIABLES: NAVIGATIONAL SYSTEM DESIGN AND ENVIRONMENTAL CONDITION

	Navigational System Design			
Environmental Condition	1	2	3	4
Favorable	1			
Thunderstorm	2	4	6	8
Heavy Fog	3	5	7	9

NOTE: The numbers within the table refer to the number of experimental condition.

The environmental conditions varied across scenarios. For those scenarios which involved *favorable environmental* conditions, the current was slack, wind was from 285°T ± 45° at 8 knots, and visibility was clear daylight. For fog *condition scenarios, the entire run* took place in extremely limited visibility, 0.1 nm in daylight. The wind was from 285°T ± 45° at 8 knots and a 2 knot flood current was present. Thunderstorms were a bit more difficult to manipulate due to their temporary nature and heavy rain characteristics. Scenarios involving thunderstorms began in conditions which were consistent with a favorable environment: 8 knot wind from 285°T ± 45° and clear daylight visibility. A 2 knot flood current was in effect throughout thunderstorm scenarios. When the vessel's position was approximately 1.25 nm from the bridge, the vessel encountered a thunderstorm. Winds increased to a mean of 40 knots from 330°T ± 45° with gusts ± 10 knots and wind *sounds became* audible on the ship's bridge. The degree of sun/ambient light was reduced to dusk levels (to stimulate heavy cloud cover), visibility was restricted to .1 nm (to stimulate heavy rain), and ship's radar displayed heavy rain clutter. These conditions remained until the scenarios were terminated. By introducing the thunderstorm at this point, the storm was encountered about .5 nm **before** the turn for all scenarios except those involving the extended

Cut A Channel. In that channel design, the storm was encountered after the turn into Cut A Channel. The storms were phased in over an approximately one minute period.

Three scenarios involved Navigational Design 1 which represents the channel and bridge as they were in May 1980 (Scenarios 1, 2, and 3). For each, the vessel was initialized abeam of buoy "C15" in the center of Mullet Key Channel and proceeded until it was clear of the bridge (see Figure 1). The Precision Electronic Navigation Aid was not operational during any of these scenarios. Environmental conditions varied from favorable (Scenario 1), to thunderstorm (Scenario 2), to fog (Scenario 3) conditions.

For all four scenarios involving Navigational System Designs 2 and 3 representing the old channel and new bridge, the vessel was initialized abeam of buoy "23" in the center of Mullet Key Channel (Scenarios 4, 5, 6, and 7). The runs were terminated when the vessel cleared all bridge structures (see Figure 2). For two scenarios the Precision Electronic Navigation Aid was operational (Scenarios 7 and 8) and for two it was not operational (Scenarios 5 and 6). Finally, two scenarios involved thunderstorm conditions (Scenarios 5 and 7) and two involved fog conditions (Scenarios 6 and 8).

For all scenarios involving Navigational System Design 4 representing the extended Cut A Channel, the initialization position was midway between buoys "19" and "21" in the center of Egmont Channel (Scenarios 8 and 9). These scenarios terminated, as did all other scenarios, when the vessel cleared all bridge structures (See Figure 3). The Precision Navigation Aid was not present for any of these scenarios, however, and the environmental conditions involved thunderstorm (Scenario 8) and fog (Scenario 9) characteristics.

Prior to making passages as part of the actual study, each pilot was given two scenarios (Scenarios A and B) designed to familiarize the pilot with several aspects of the study. These included the handling characteristics of the vessel, the Precision Electronic Navigation Aid, the environmental conditions, the extended Cut A Channel design, and the new Sunshine Skyway Bridge. Scenario A was a passage through the new bridge/existing channel model of Tampa Bay (See Figure 2). The initialization and termination points were the same as those for the other scenarios using this model of Tampa Bay (Scenarios 4, 5, 6, and 7). The environmental conditions were favorable and the PENA was available. Scenario B was a passage through the extended Cut A channel model of Tampa Bay (see Figure 3) with initialization and termination locations the same as Scenarios 8 and 9. The PENA was also available during this scenario. The environmental conditions were favorable upon initialization but during the passage a thunderstorm was introduced in the same way as during test scenarios. In addition, fog was introduced at some point during the scenario.

Both familiarization scenarios were conducted like actual test scenarios, e.g., the pilot was completely in command, except that CAORF staff were present to answer any questions the pilot had and to help explain the PENA.

Specific operating parameters for all eleven scenarios are presented in Appendix D. It should be noted that a scenario was terminated if a head on collision with the bridge was imminent. Due to the realism of the simulation it was decided not to allow such contact since it might have affected a pilot's subsequent performance.

4.5 PILOT ORIENTATION

4.5.1 Introduction and Briefing

Upon arrival at CAORF, pilots were welcomed and briefed on the purposes of the study. The briefing was given both orally and in writing and is contained in Appendix E.

In addition to this general briefing, prior to each scenario pilots were informed regarding the particulars of the scenario they were about to encounter. These particulars included:

- The navigational system design (channel configurations, aids to navigation and bridge) in effect.
- Environmental conditions - wind, current, visibility and fog or thunderstorm conditions.
- Whether the Precision Electronic Navigation Aid would be available.
- Vessel initialization conditions.

Since conditions remained constant for all but thunderstorm scenarios, this prepassage briefing was sufficient. For thunderstorm scenarios, pilots were told what initialization environmental conditions were and that there were intense thunderstorms in the area. They were not told specifically when or if they would experience one. This information would come during the passage from the "lookout".

It must be emphasized that the participation of pilots in this study did **not** constitute an endorsement of vessel pilotage under the environmental conditions being investigated. Under most circumstances, Tampa Bay Pilots would not bring a vessel through the Sunshine Skyway Bridge under conditions as severe as those modelled in the simulation. Pilots were asked to do so for the purposes of this risk mitigation research (see briefing materials in Appendix E).

4.5.2 Debriefing

Debriefing was principally accomplished with the use of debriefing questionnaires to elicit pilot's evaluation of scenarios experienced. The Pilotage Evaluation Rating Scale was given to pilots following each scenario. This rating scale is contained in Appendix C.

Final debriefing was accomplished after *all* of a *pilot's* runs had been completed. This debriefing combined an open ended questionnaire format and discussions with CAORF staff. The questionnaire (contained in Appendix C) required a global assessment of the conditions evaluated and the quality of the simulation.

CHAPTER 5

RESULTS

5.1 OVERVIEW OF THE DATA ANALYSIS

The analysis of data for this study proceeded in phases. The first phase was the determination of the effects of the different adverse environmental conditions (thunderstorm and fog) on vessel proximity and controllability measures. That is, did the thunderstorms result in vessel behavior which was significantly different from that observed when fog conditions were in effect? In addition, were the effects of the environmental conditions different depending upon the navigational system design? Failure to detect differential environmental effects across varying navigational system design (called a statistical interaction) would enable a direct comparison between the navigational system designs alone.

The second and most important phase of the analysis was the evaluation of the effect of navigational system designs on vessel proximity to bridge structures. The third phase of the analysis was concerned with the effect of navigational system designs on vessel controllability measures. Controllability variables were analyzed for the purpose of examining the degree to which pilots had to maneuver their vessels in order to maintain the observed proximity of their vessels from bridge structures.

The fourth and final phase of the data analysis was the evaluation of pilot ratings of the experimental conditions they experienced.

It should be noted that the analyses to be described involved many dependent variables. Definitions of these variables were presented in Paragraph 4.3.2 Dependent Variables. The reader is referred to that section for an explanation of the meaning of any of these variables.

The principal way of presenting the results is in terms of descriptive statistics for each variable in the analyses. Two types of descriptive statistics are provided: means and standard deviations. The mean reflects the arithmetic average of the variable under discussion and the standard deviation provides an indication of the extent to which individual scores varied around the mean.

While average values for the various measures provide a quantitative depiction of how performance differed across conditions, one must be cautious in drawing conclusions regarding the effects of the experimental conditions from these values alone. Therefore, the results are also presented in terms of the outcomes of statistical tests performed on the data. For the reader unfamiliar with inferential hypothesis testing procedures, a discussion of these statistical techniques, and of the reasons for their use, follows.

Performance of a task as complex as piloting a ship is certain to vary, not only from pilot to pilot, but for the same pilot from one passage to the next, even under similar external conditions. An example based on the present study will illustrate why such variability is troublesome. Suppose that a small group of pilots made bridge passages in navigation system designs "A" and "B" and that the closest point of approach (CPA) to the bridge averaged 50 feet more for design "A" than for design "B". Should design "A" be declared the safer design? The existence of variability in individual scores around their group average makes it necessary to consider the possiblity that designs "A" and "B" do not differ **significantly** in CPA and that the observed difference in performance was due only to chance. In other words, it is possible that the result is not reliable; it would not necessarily be found again if the experiment were repeated.

How then can one avoid making incorrect decisions or false claims when interpreting a limited amount of data? The possibility of error cannot be totally eliminated, but it can be controlled. A statistical technique known as the Analysis of Variance (ANOVA) allows researchers to specify an acceptable probability of this error, i.e., the probability that the observed differences are simply due to chance and not reliable differences between the conditions being compared. This probability is called the significance level and an observed difference between the averages of the experimental conditions is considered reliable only if the probability of its having occurred by chance is less than the acceptable probability of error. For example, if the acceptable error rate is set at .05 and the observed difference has a significance level below that rate then the difference observed would be considered statistically significant. That is, it would have less than a .05 (1 in 20) probability of being due to chance. The ANOVA yields an F statistic related to each independent variable under examination and has associated with it (in conjunction with other statistical parameters) an error probability that permits an evaluation of the likelihood that the observed differences were due to chance.

In the statistical analyses which follow, the F statistics resulting from the ANOVA are reported along with their associated error rates (significance levels). For the purposes of this study, when error rates were between .10 and .05, the results were considered marginally significant; when error rates were less than .05 the results were considered significant. The reader should keep in mind that the error rate refers to the probability that the observed differences between averages (such as between two navigational system designs) are due to chance and do not reflect reliable, statistically significant differences.

5.2 THE EFFECTS OF THE ENVIRONMENT ON VESSEL PERFORMANCE

The initial set of data analyses was directed towards determining the effects of the weather conditions on vessel performance with respect to both proximity and controllability variables. Since the favorable condition was combined with only one navigational system design, it was excluded from these analyses. Instead, the comparison made was between the fog and thunderstorm conditions.

Means and standard deviations for the proximity variables as a function of Environmental Condition (EC) and Navigational System Design (NSD) are presented in Table 6. Similar data for controllability variables are presented in Table 7. Differences among the individual means for all the dependent variables are represented graphically in the histograms in Figures 7 through 19. Note that these histograms do not include the full scale for each dependent variables. The histograms are used here only to illustrate the difference between means and therefore these differences sometime appear exaggerated.

The effects of environmental condition on each of these dependent variables was tested in a Two Factor Repeated Measures Analysis of Variance (Kirk, 1968). The two factors were Navigational System Design, having four levels, (1, 2, 3, and 4), and Environmental Condition, having two levels (thunderstorm and fog). Since each pilot participated in each experimental condition, pilots served as the blocking variable (variable on which measures were repeated). Navigational System Design was incorporated as a separate factor, rather than being averaged out, since there was a possibility that the environmental conditions could have had differing effects depending on the navigational system design in which they occurred. Such a finding would have been important since it would have required separate consideration of thunderstorm and fog conditions when differences between navigational system designs were discussed. An effect such as this would be reflected in statistically significant interaction effects in the ANOVAs.

A total of 13 ANOVAs were performed, one for each dependent variable listed in Tables 6 and 7. The individual summary tables for each ANOVA are presented in Appendix F. A general summary of the F statistics and related significance levels of all ANOVAs are presented in Table 8 for the proximity variables and Table 9 for the controllability variables.

An examination of F statistics in Table 8 indicates that there were significant differences between thunderstorm and fog conditions on CPA and variation in ship's distance from the bridge but not on average distance from the bridge. More importantly, there were no significant interactions between the Environmental Condition and Navigational System Design variables. Significant differences were also found among the navigational system designs, however, these will not be discussed in this section since the following sections focus on these differences.

The nature of the significant environmental effect in the analyses of CPA and variation in ship's distance from the bridge can be seen in Figures 7 and 9 respectively. In each navigational system design, transits under thunderstorm conditions resulted in closer CPAs to the bridge than those under fog conditions. The overall average CPA in fog was approximately 246 feet while during thunderstorm transits the average was 200. The same pattern held for average distances from the bridge, i.e., vessels came closer to the bridge during thunderstorm transits, but these differences were not statistically significant. Vessels, however, were found to be significantly more variable in ship's distance from the bridge during thunderstorms (see Figure 9) indicating a greater range of vessel distances around their average distances away from the bridge. Vessels were on

TABLE 6. DESCRIPTIVE STATISTICS FOR VESSEL PROXIMITY MEASURES AS A FUNCTION OF ENVIRONMENTAL CONDITION AND NAVIGATIONAL SYSTEM DESIGN

		THUNDERSTORM Navigational System Design				FOG Navigational System Design			
Dependent Variable		1	2	3	4	1	2	3	4
Closest Point of Approach to Bridge	M	120.10	194.67	286.75	201.56	174.95	248.00	307.22	255.69
	SD	91.79	104.59	63.48	156.58	78.75	59.38	56.63	111.56
Average Distance of Ship from Bridge	M	154.72	229.37	322.28	221.07	244.76	259.05	334.92	271.51
	SD	84.87	96.20	68.74	166.02	143.35	56.66	48.25	96.94
Variation in Ship's Distance from Bridge	M	27.13	28.71	25.17	24.20	9.84	8.69	23.07	12.76
	SD	9.98	15.08	18.10	10.61	2.74	6.25	9.20	13.72

NOTES: 1. All of the above values are in feet.
2. N = 7 for each statistic.

average nearly twice as variable during thunderstorm passages as compared with fog passages (26 feet and 14 feet respectively).

Table 9 provides the F statistics and significance levels for vessel controllability variables. It can be concluded from these statistics that the environmental conditions did not have a great effect on vessel controllability. The only significant differences were found on the two swept path variables. No differences were observed on yawing characteristics, rudder activity, or distance from channel centerline variables. In addition, it is important to note that no significant interactions were detected.

The effects of the environmental conditions on swept path measures can be seen in Figures 13 and 14. The average swept path during thunderstorms was 269 feet as compared with only 219 feet during fog transits. In addition, vessels were approximately twice as variable in their swept paths during thunderstorm passages. This finding was expected since thunderstorms were associated with high and variable winds while fog conditions were not. These values reflect pilot corrections for the thunderstorm's aerodynamic effects on the vessel.

As with the proximity variables analyses, significant effects of navigational system design will not be discussed in this section.

5.3 THE EFFECTS OF NAVIGATIONAL SYSTEM DESIGNS ON VESSEL PROXIMITY TO BRIDGE STRUCTURES VARIABLES

The effects of the navigational system designs on vessel proximity to bridge structures variables were of primary importance. The purpose of the analyses to be described in this section was to evaluate these effects. Since there were no significant interactions between Environmental Condition and Navigational System Design, as reported in the previous section, scores for the thunderstorm and fog conditions were averaged for each navigational system design. These scores provided a single measure characterizing performance in each navigational system design under adverse conditions. This allowed for a more sensitive test of the effect of navigational system design as well as facilitating comparisons with the data collected in Navigational System Design 1 under favorable environmental conditions (NSD1F). Note that this condition, in conjunction with Navigational System Design 1 under adverse environmental conditions (NSD1A), was used as a yardstick against which to evaluate the relative safety provided by alternative navigational system designs, referred to as NSD2, NSD3, and NSD4, under adverse weather. Refer to Paragraph 4.3.3 for further clarification of this point.

To augment the evaluation of vessel proximity to bridge structures variables, a composite envelope track plot was produced for each experimental condition under investigation. The plots were produced from data collected by

TABLE 7. DESCRIPTIVE STATISTICS FOR VESSEL CONTROLLABILITY MEASURES AS A FUNCTION OF ENVIRONMENTAL CONDITION AND NAVIGATIONAL SYSTEM DESIGN

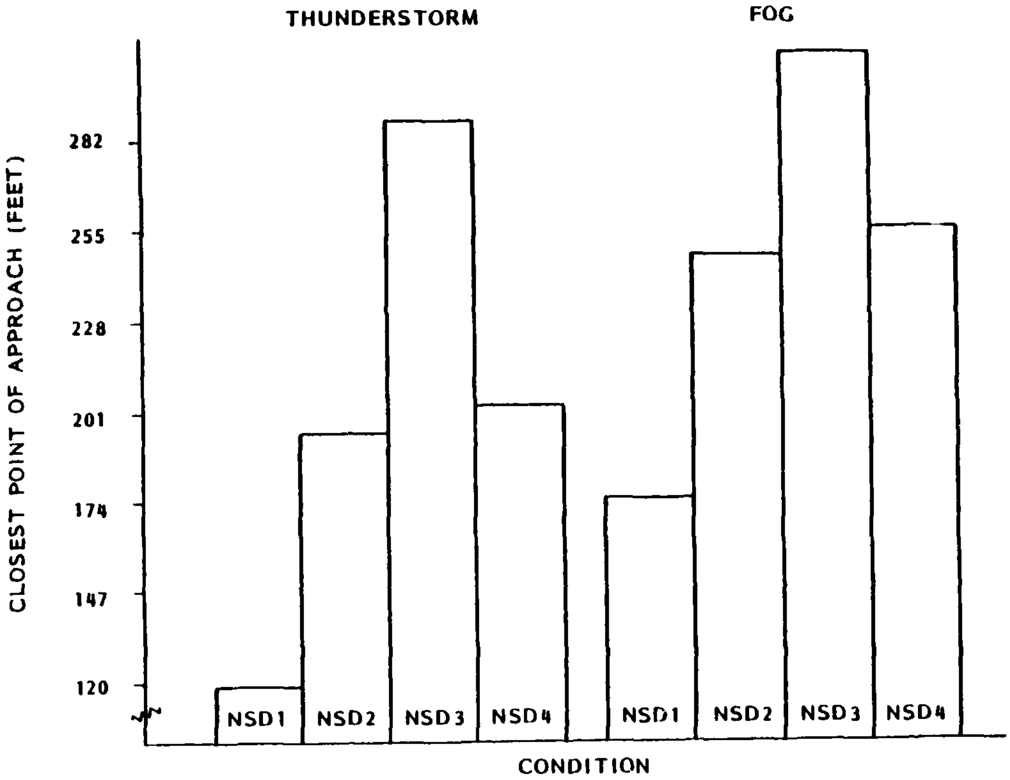
		THUNDERSTORM Navigational System Design				FOG Navigational System Design			
Dependent Variable		1	2	3	4	1	2	3	4
Variation in Heading (deg.)	M	2.30	2.37	5.50	1.93	2.47	1.53	3.38	1.52
	SD	1.13	1.31	3.25	0.99	1.39	0.56	2.65	1.49
Average Absolute Rate of Turn (deg./sec.)	M	0.59	0.50	0.52	0.47	0.62	0.41	0.46	0.36
	SD	0.15	0.06	0.26	0.15	0.12	0.16	0.21	0.12
Variation in Rate of Turn (deg./sec.)	M	0.39	0.43	0.37	0.40	0.42	0.38	0.41	0.39
	SD	0.05	0.03	0.08	0.05	0.04	0.05	0.04	0.07
Average Swept Path (feet)	M	260.61	277.23	303.20	238.90	222.24	203.20	259.47	194.18
	SD	50.01	71.04	20.00	89.58	36.19	27.77	21.63	26.62
Variation in Swept Path (feet)	M	36.08	36.97	64.12	24.78	28.55	23.25	42.96	15.16
	SD	18.68	19.39	22.69	8.76	12.68	9.12	19.23	11.93
Average Absolute Rudder Angle (deg.)	M	10.95	9.28	12.43	10.40	10.47	8.27	11.37	6.21
	SD	5.13	2.95	4.02	8.59	3.61	3.40	4.68	3.89
Variation in Rudder Angle (deg.)	M	7.40	7.27	9.94	5.94	7.03	7.38	7.50	4.68
	SD	2.76	3.40	2.72	1.17	2.74	1.39	2.11	2.20
Number of Rudder Reversals	M	4.71	4.42	4.00	4.57	3.85	5.42	4.14	3.28
	SD	2.21	0.97	1.41	2.37	1.67	1.51	1.77	1.97
Average Deviation from Centerline (feet)	M	228.04	199.70	154.55	206.90	213.37	197.86	149.50	130.69
	SD	92.15	98.51	46.20	203.12	92.78	62.38	46.53	74.64
Variation in Deviation from Centerline (feet)	M	45.71	48.59	82.59	54.41	55.26	35.65	85.36	31.68
	SD	21.36	32.17	30.27	48.94	24.03	20.03	28.29	28.97

NOTE: N = 7 for each statistic.

computer every 15 seconds pertaining to each vessel's position in the channel, rudder angle, and heading. These data were then integrated and a computer generated graphic display of each vessel's position relative to channel boundaries and bridge structures was produced. Since a total of seven transits were made in each experimental condition, seven vessel trackplots are displayed in each composite plot. The plots, therefore, show the entire area of the waterway used by all pilots. This area is referred to as the composite envelope in which all transits were contained.

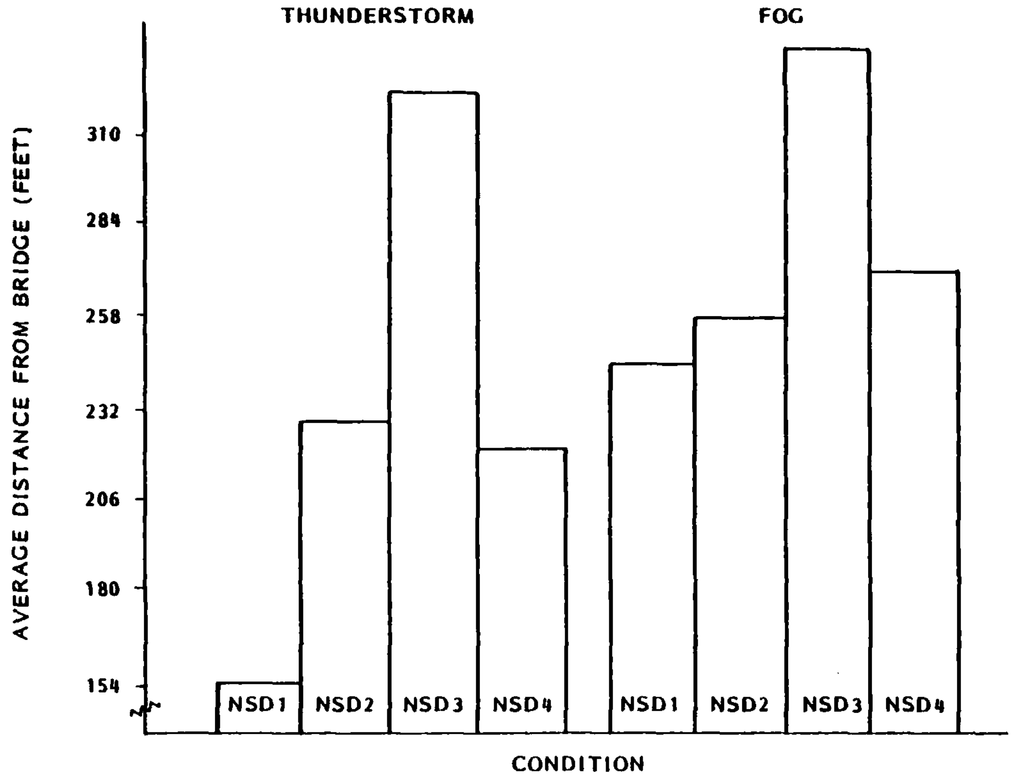
Means and standard deviations for each proximity variable as a function of Navigational System Design are presented in Table 10. The composite envelope track plots for each navigational system design as a function of environmental conditions (thunderstorm, fog, and favorable) are presented in Figures 20 to 28.

Fog and thunderstorm conditions are presented separately in these plots rather than being averaged simply because the plots depict **actual** transits while averages represent statistical summaries of pairs of transits (i.e., averaged



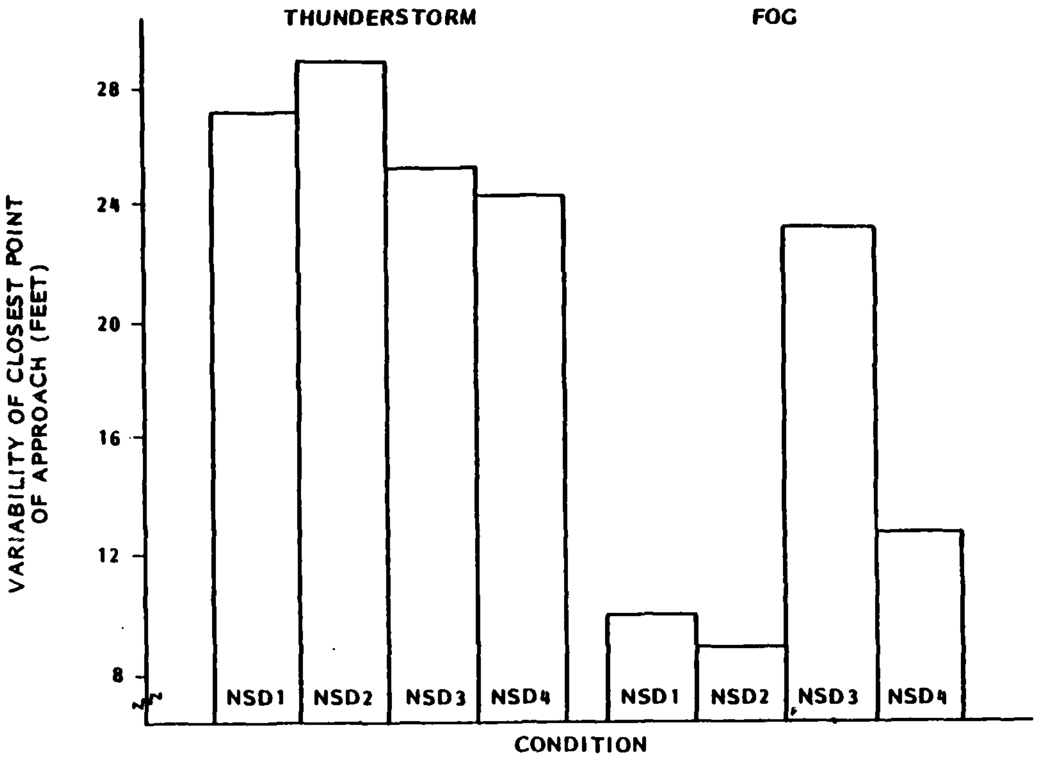
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 7. Closest Point of Approach in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



NOTE : Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 8. Average Distance from Bridge in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 9. Variability of Closest Point of Approach in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).

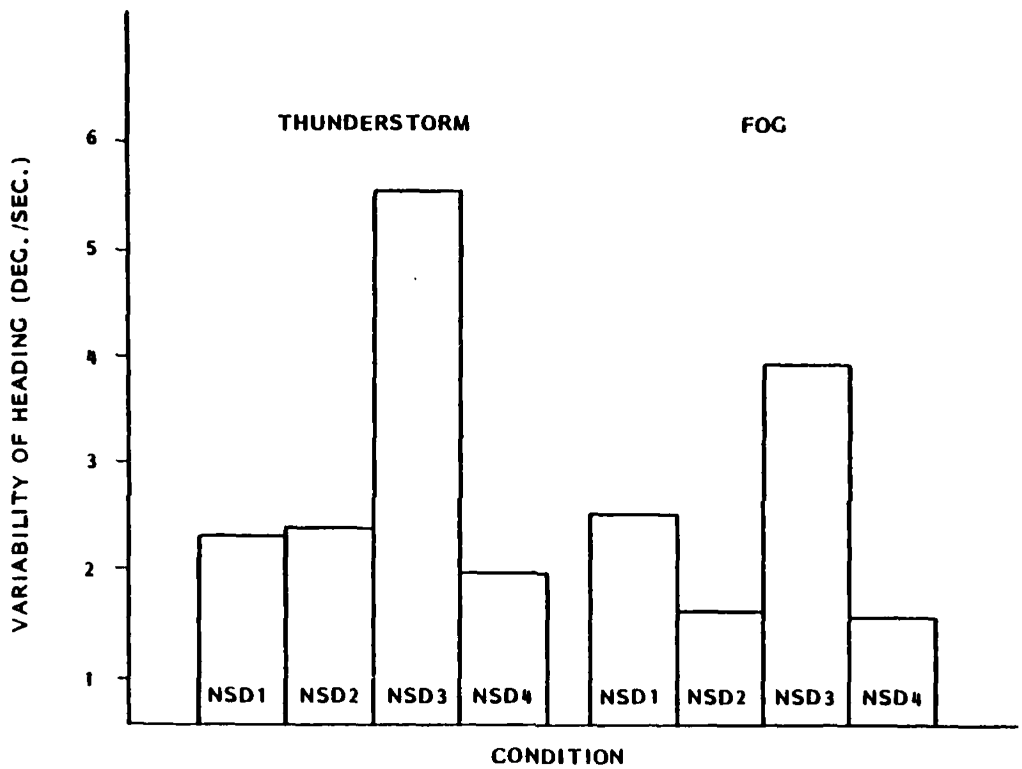


Figure 10. Variability of Heading in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).

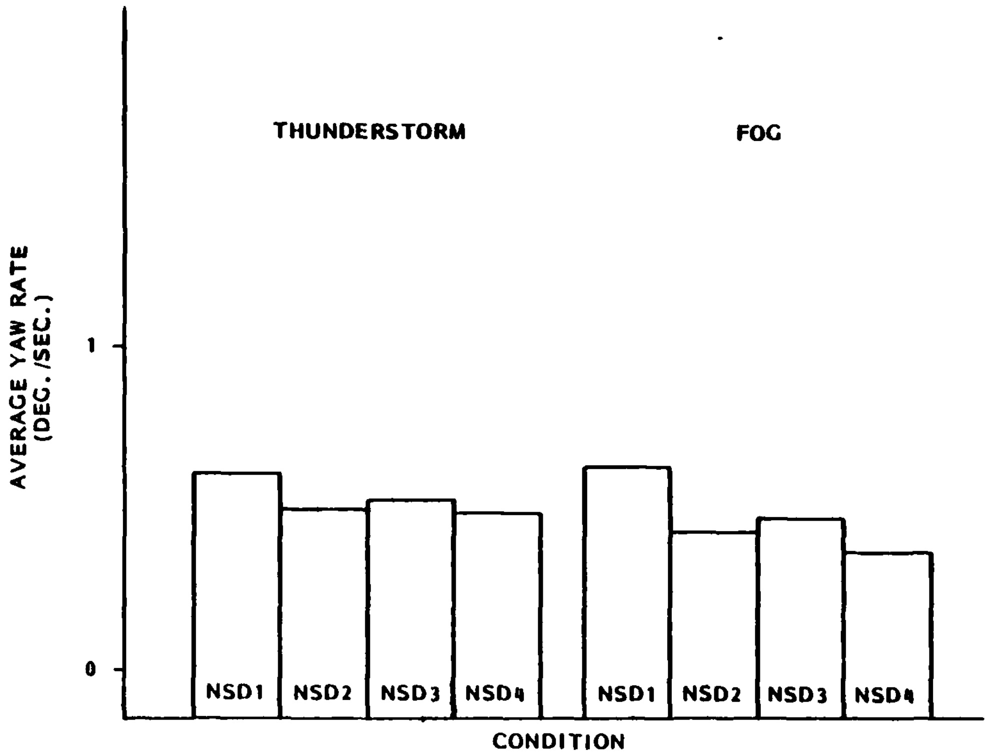


Figure 11. Average Yaw Rate in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition. (N = 7).

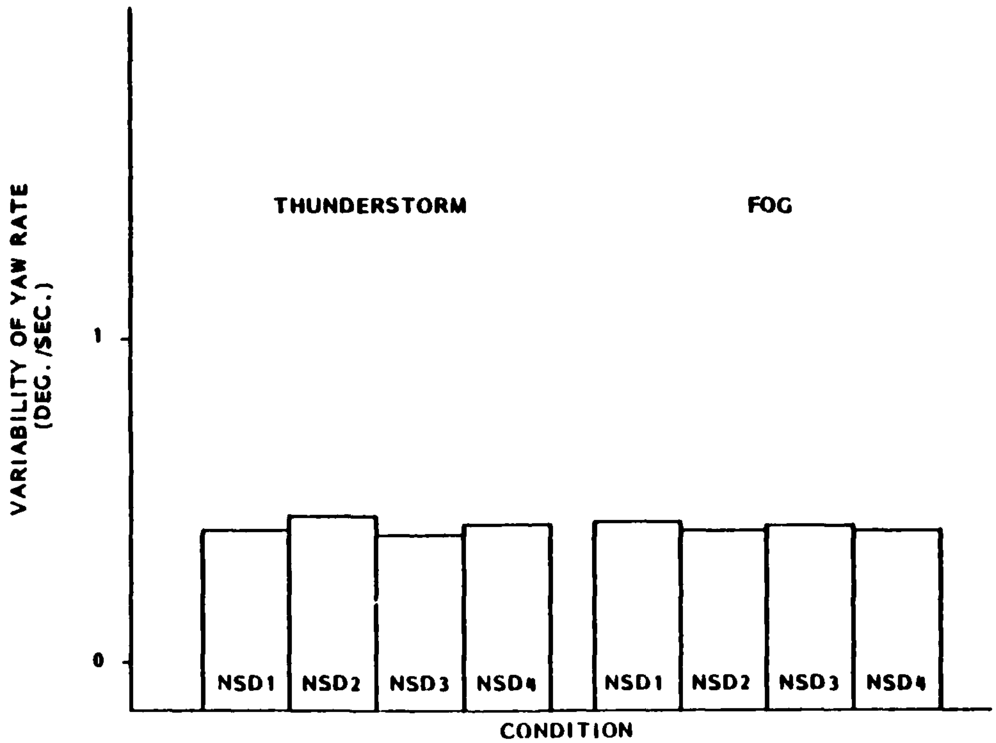
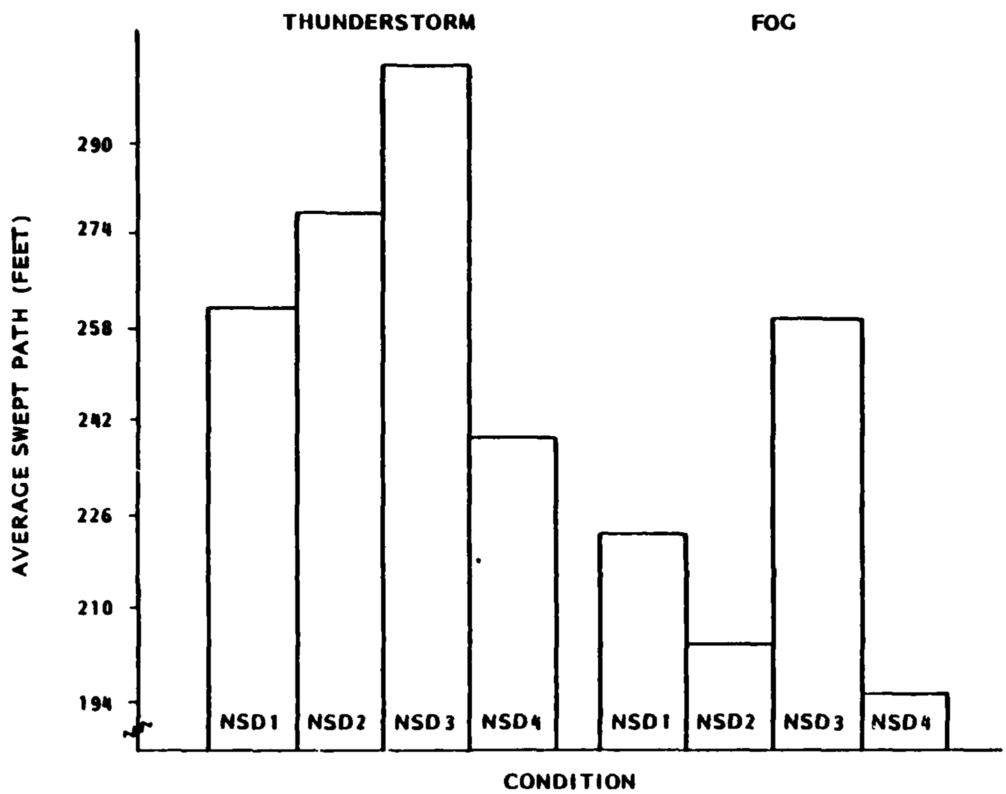
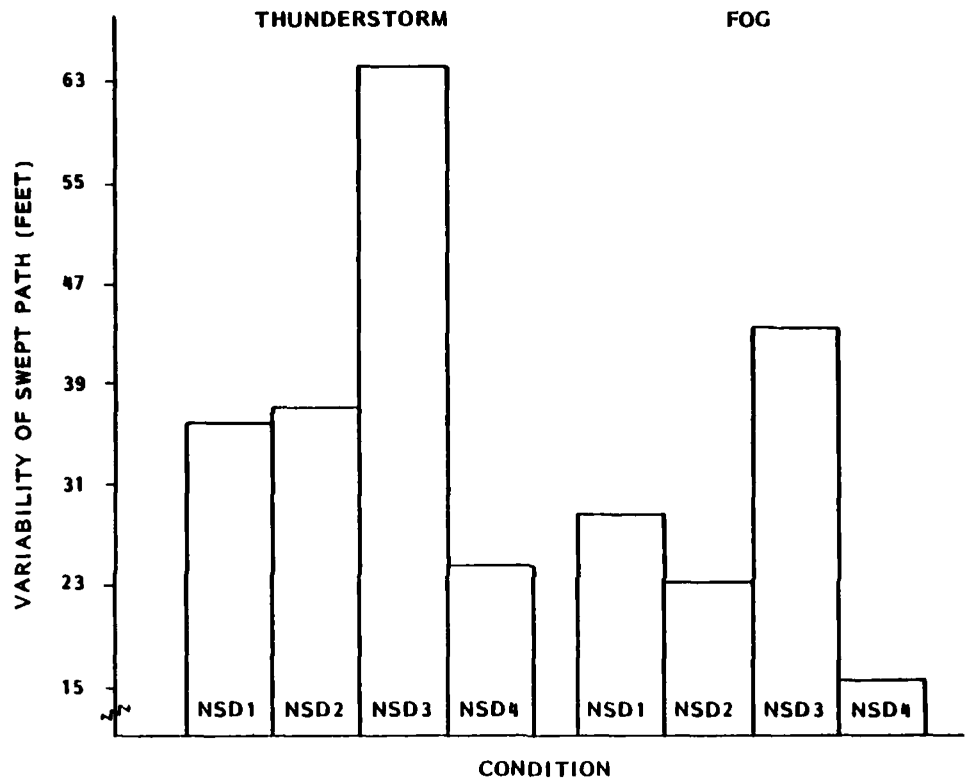


Figure 12. Variability of Yaw Rate in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



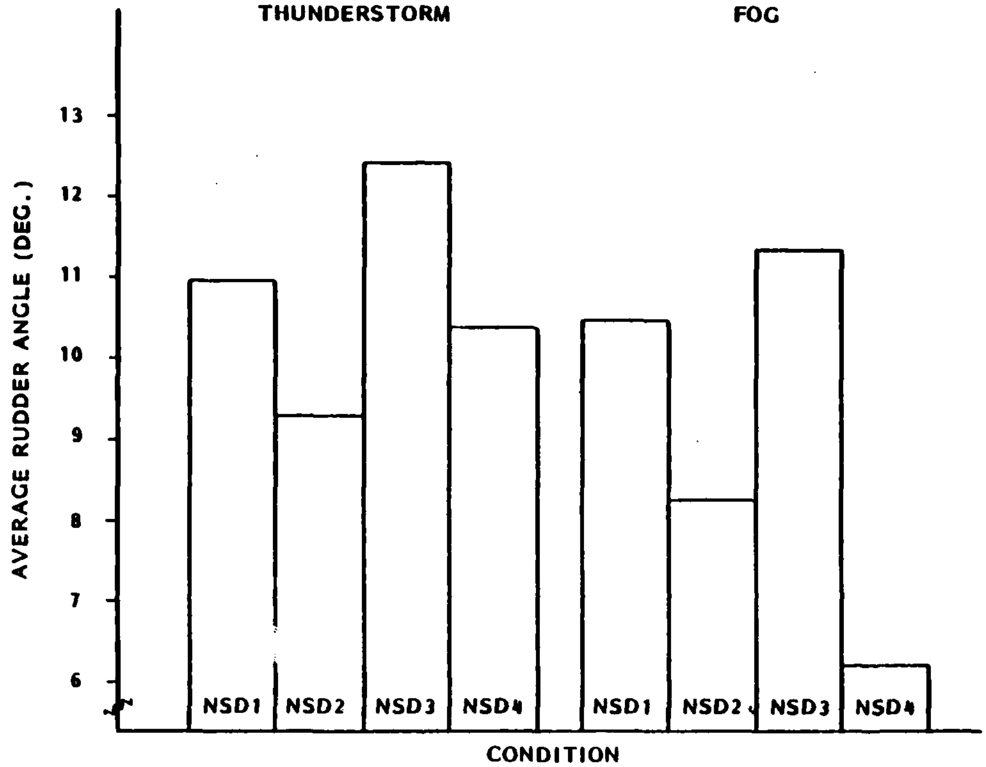
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure

Figure 13. Average Swept Path in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



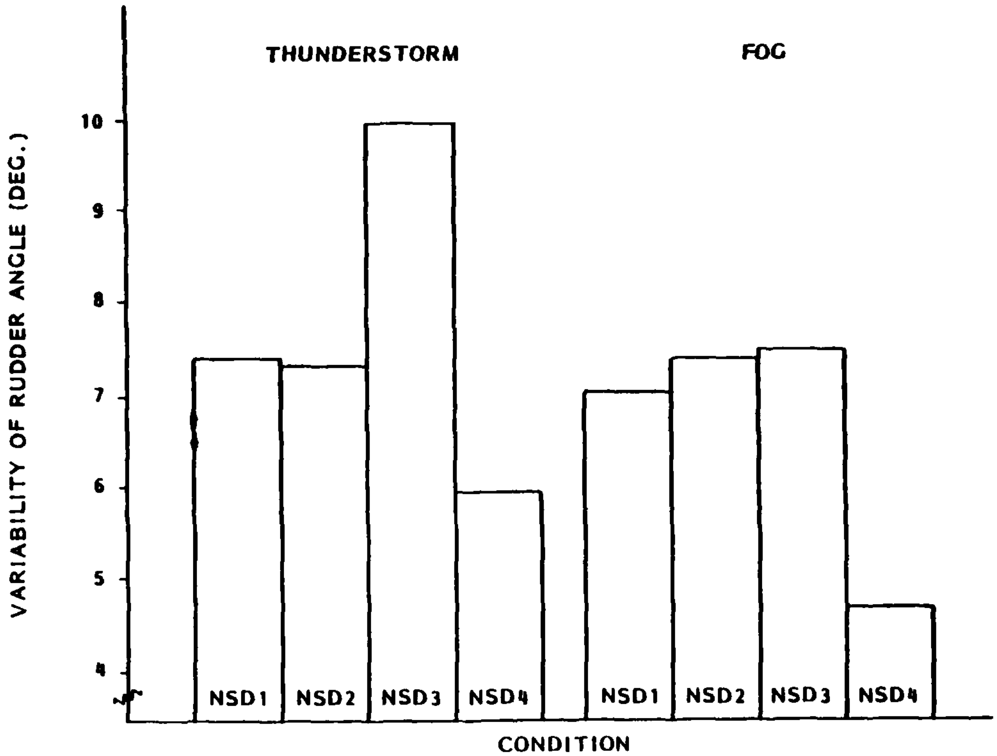
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure

Figure 14. Variability of Swept Path in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



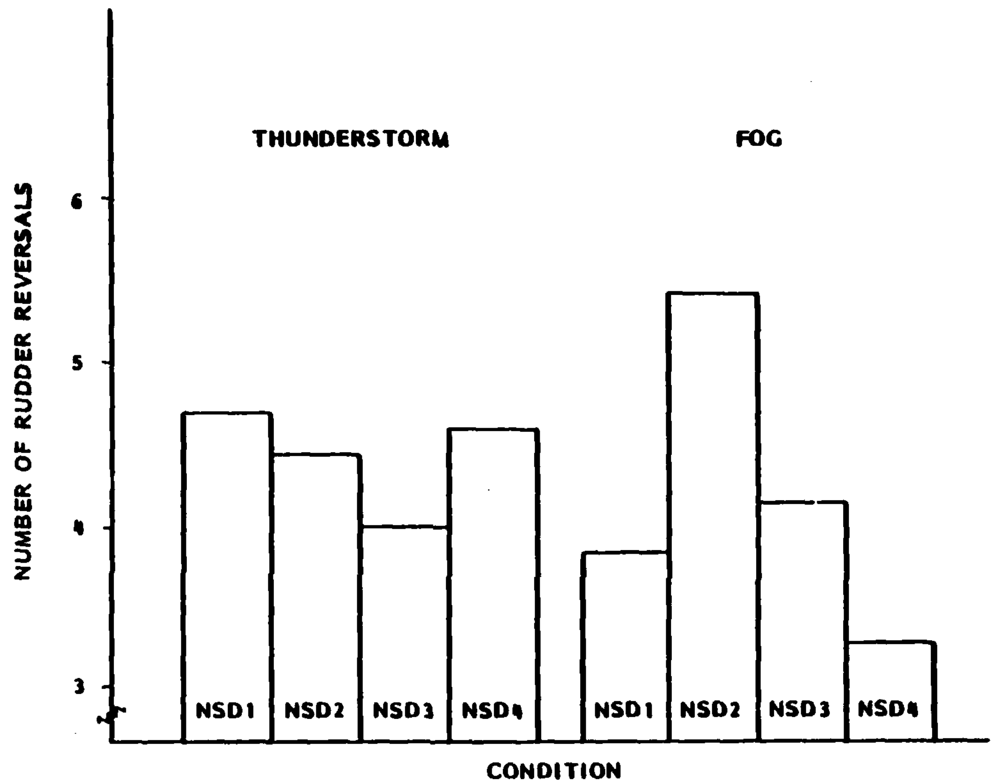
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 15. Average Rudder Angle in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



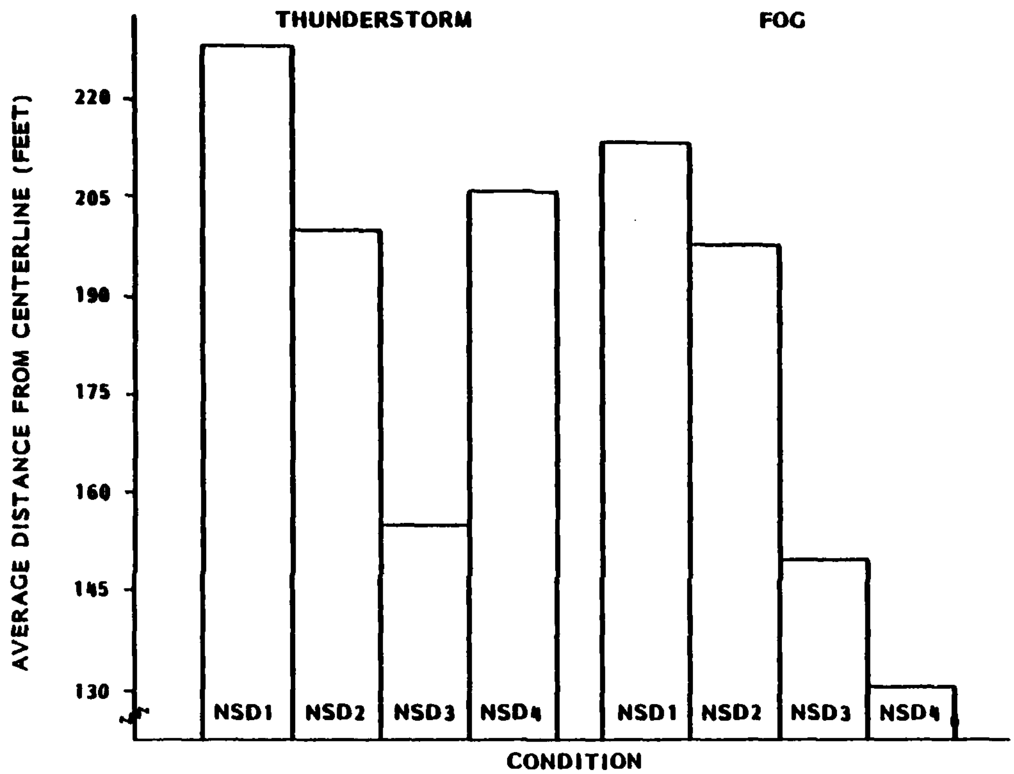
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 16. Variability of Rudder Angle in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



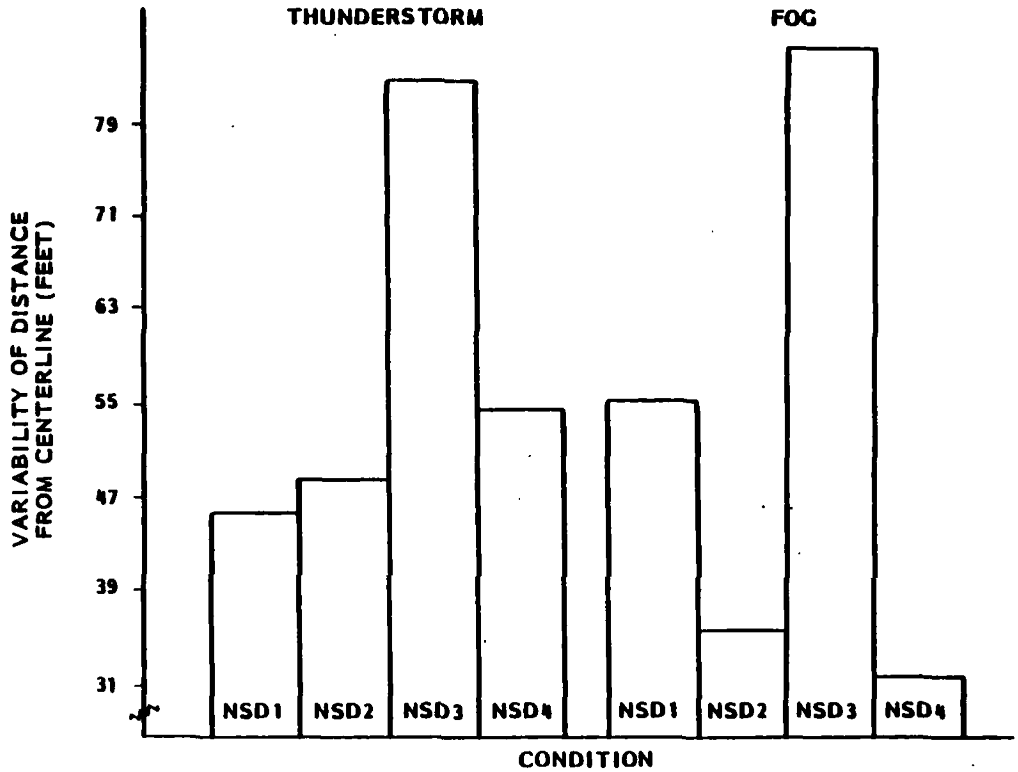
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 17. Number of Rudder Reversals in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 18. Average Distance From Centerline in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 19. Variability of Distance From Centerline in Each of the Four Navigational System Designs Under Thunderstorm and Fog Conditions. Bars Represent the Mean Value for Each Condition (N = 7).

TABLE 8. VESSEL PROXIMITY MEASURES ANALYSIS OF VARIANCE SUMMARY TABLE OF ENVIRONMENTAL EFFECT[a]

Dependent Variable	Env. Cond. (E)	Nav. Sys. Des. (N)	Interaction (NE)	Appendix Table
Closest Point of Approach to Bridge	3.00*	5.37***	< 1	F1
Ave. Distance of Ship from Bridge	2.68	3.70**	< 1	F2
Var. of Ship's Distance from Bridge	16.38***	< 1	1.593	F3

NOTES: 1. Individual ANOVA Summary Tables can be found in Appendix F according to the reference numbers listed in the table.

2. Significance Levels: * = $p < 0.10$
** = $p < 0.05$
*** = $p < 0.01$

No * indicates no significant effect.

[a] Values reported are F ratios.

TABLE 9. VESSEL CONTROLLABILITY MEASURES ANALYSIS OF VARIANCE SUMMARY TABLE OF ENVIRONMENTAL EFFECT[a]

Dependent Variable	Env. Cond. (E)	Nav. Sys. Des. (N)	Interaction (NE)	Appendix Table
Ave. Yaw Rate	2.21	4.37***	< 1	F4
Var. of Yaw Rate	< 1	< 1	< 1	F5
Var. of Heading	2.02	8.19***	< 1	F6
Ave. Swept Path	16.33***	4.68***	< 1	F7
Var. Swept Path	9.42***	11.08***	< 1	F8
Ave. Rudder Angle	1.79	1.77	< 1	F9
Var. of Rudder	2.40	4.81***	< 1	F10
Rudder Reversals	< 1	1.03	1.39	F11
Ave. Dev. Centerline	< 1	1.27	< 1	F12
Var. Dev. Centerline	< 1	5.52***	< 1	F13

NOTES: 1. Individual ANOVA Summary Tables can be found in Appendix F according to the reference numbers listed in the table.

2. Significance Levels: * = $p < 0.10$
** = $p < 0.05$
*** = $p < 0.01$

No * indicates no significant effect.

[a] Values reported are F ratios.

TABLE 10. DESCRIPTIVE STATISTICS FOR PROXIMITY MEASURES IN NAVIGATIONAL CONDITIONS COMPARISONS

Dependent Variable		Navigational Condition 1F	1	2	3	4
Closest Point of	M	199.87	147.52	221.33	296.99	228.62
Approach to Bridge	SD	48.48	53.27	59.92	35.86	109.42
Average Distance of	M	213.47	199.74	244.21	328.60	246.29
Ship from Bridge	SD	51.22	96.24	53.72	35.24	107.25
Variation in Ship's	M	13.03	18.49	18.70	24.12	18.48
Distance from Bridge	SD	8.31	4.22	7.17	9.95	9.69

NOTE: N = 7 for each statistic.

over thunderstorm and fog transits) made by each pilot within each navigational system design.

To determine whether differences among navigational system designs were significant, the data were analyzed in a Single Factor Repeated Measures ANOVA (Kirk, 1968). Navigational System Design was the single factor and had five levels (NSD1F, NSD1A, NSD2, NSD3 and NSD4). Again pilots served as the blocking variable. A total of three analyses were performed, one for each of the dependent variables listed in Table 10. A summary of the F statistics is provided in Table 11. The individual ANOVA Summary Tables for each analysis are contained in Appendix G.

Statistically significant differences among navigational system designs were found on two of the three proximity variables: CPA and average distance from bridge. The mean CPA of NSD3, the design incorporating the precision electronic navigation aid, was greater than any of the other designs evaluated. Figure 29 provides a graphic display of this difference. Vessels averaged a CPA of approximately 297 feet from the replacement Sunshine Skyway Bridge. This was an average of 68 feet better than the next best condition (NSD4, the extended Cut A Channel design). Interestingly, there was little difference in CPA between NSD4 and NSD2 (the existing channel and aids to navigation design with the new bridge but no PENA). The only design difference between NSD2 and NSD3 was the PENA, and the CPA in NSD3 was 76 feet further away from the bridge than NSD2. This difference, therefore, can be directly attributed to the PENA. The worst condition was the design as it existed circa 1980 (NSD1F and NSD1A). Under adverse conditions average CPA was 148 feet and under favorable conditions nearly 200 feet. Hence all three alternative designs resulted in greater CPAs under adverse conditions than the 1980 design under favorable conditions (NSD1F). The PENA design (NSD3) was associated with CPAs almost 100 feet greater than NSD1F.

An important piece of proximity information not directly reflected in the mean CPAs is the number of bridge "contacts" which occurred in each design. These data are most easily obtained by inspecting the composite track plots (Figures 20 - 28). It is apparent that three bridge contacts took place during the experiment, one in NSD1 (Figure 21) and two in NSD4 (Figure 27). All three occurred under thunderstorm conditions. (The CPAs for all three were defined as zero, even though in two instances the scenarios were terminated prior to any contact).

CPAs reflect the single closest distance to bridge structures and therefore do not represent typical vessel distances from the bridge. This is provided by analyzing average distances. Figure 30 is a graphic display of the differences among the navigational system designs in terms of average distances from bridge structures. Note the close similarity in the pattern of results between Figure 29 (CPA) and 30 (average distance). NSD3 was again significantly greater in average distance from the bridge than NSD2 and NSD4. NSD2 and 4 were nearly the same and NSD1F and NSD1A were lowest in average distance from bridge. NSD3, using the PENA, resulted in average vessel distances from the bridge approximately 83 feet greater than any other condition and 116 feet greater than the 1980 design under favorable conditions.

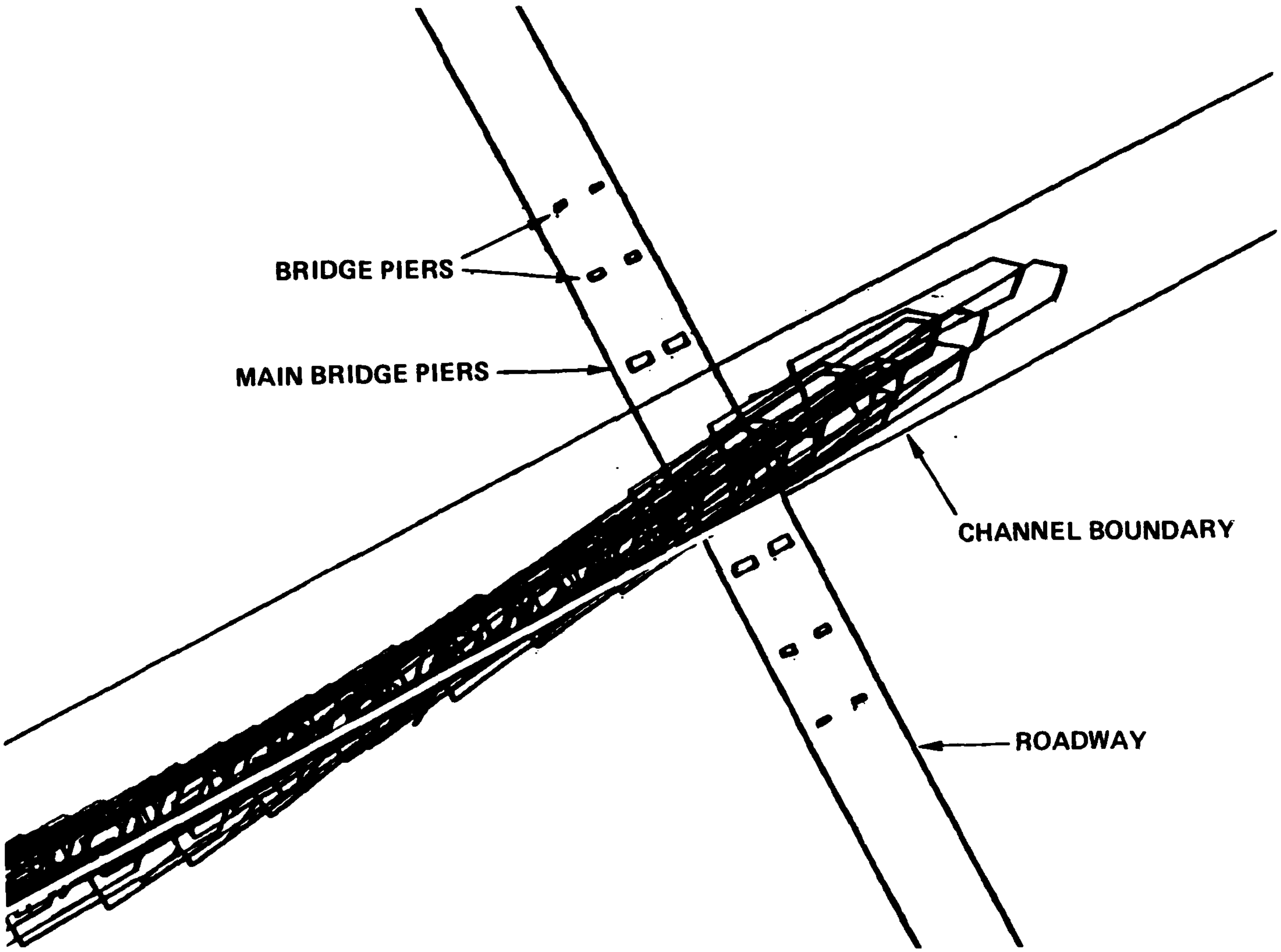


Figure 20. Composite Track Plot of Passages in Navigational System Design 1 – Favorable Conditions

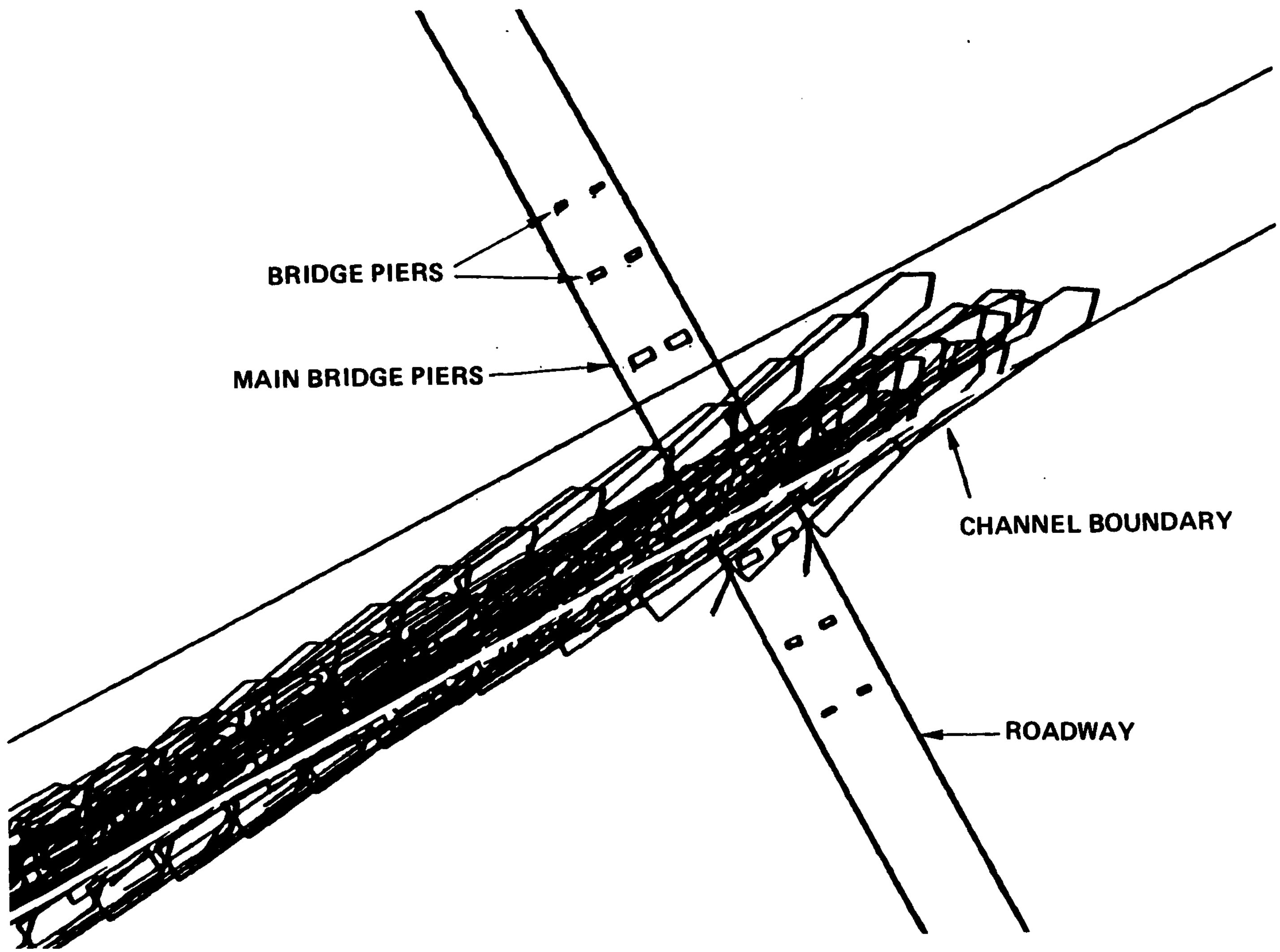


Figure 21. Composite Track Plot of Passages in Navigational System Design 1 – Thunderstorm Conditions

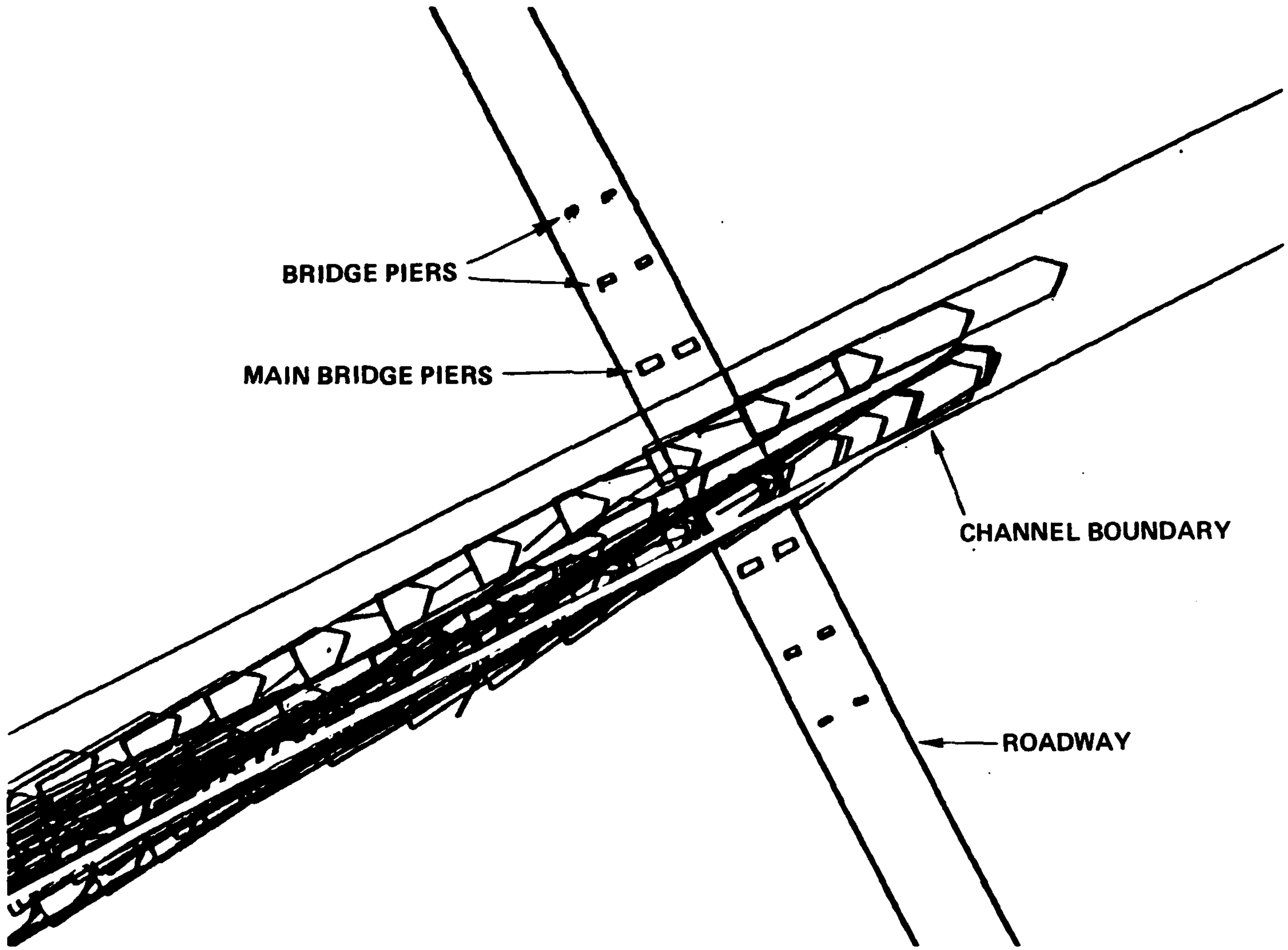


Figure 22. Composite Track Plot of Passages in Navigational System Design 1 – Fog Conditions.

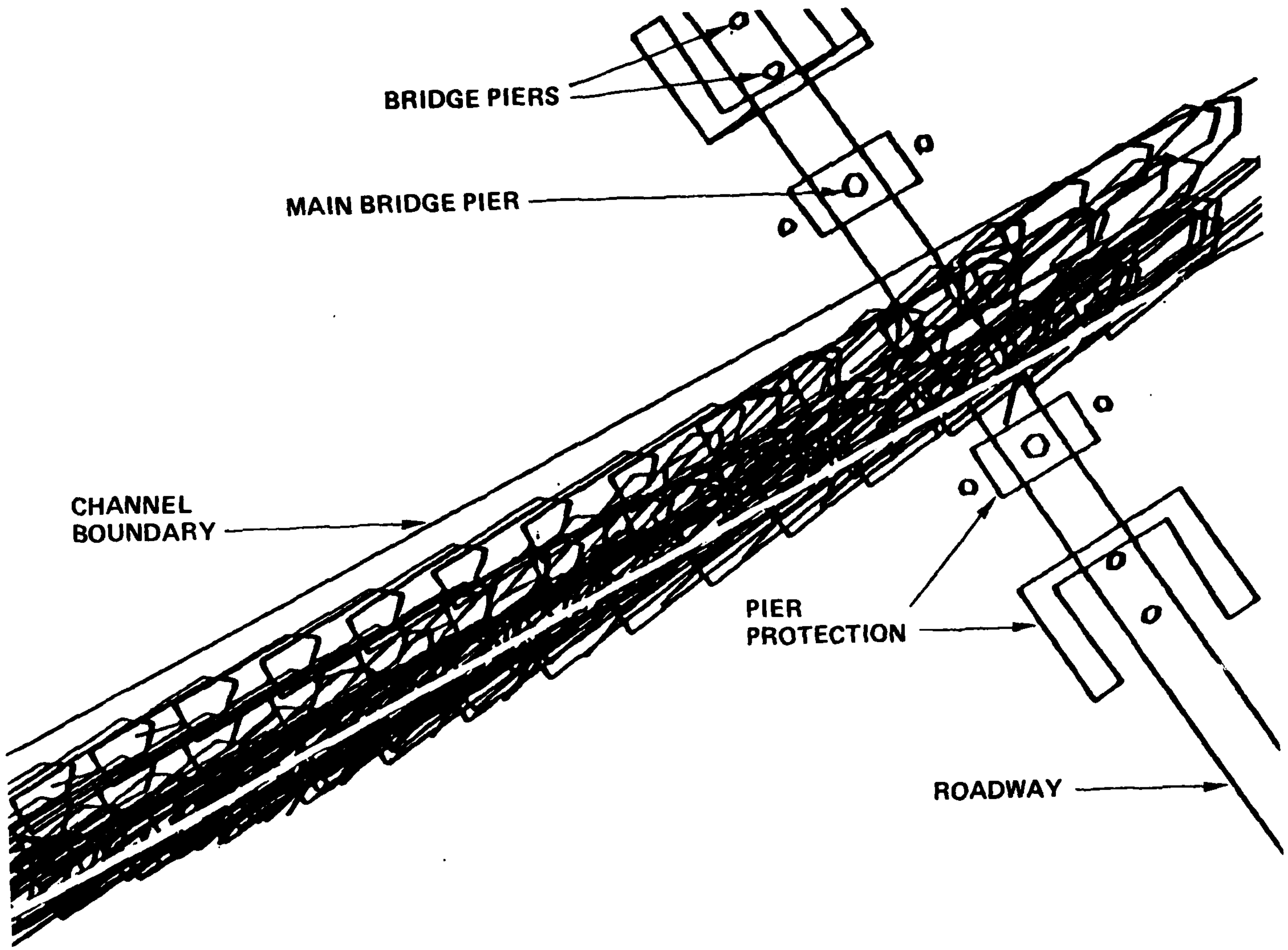


Figure 23. Composite Track Plot of Passages in Navigational System Design 2 - Thunderstorm Conditions.

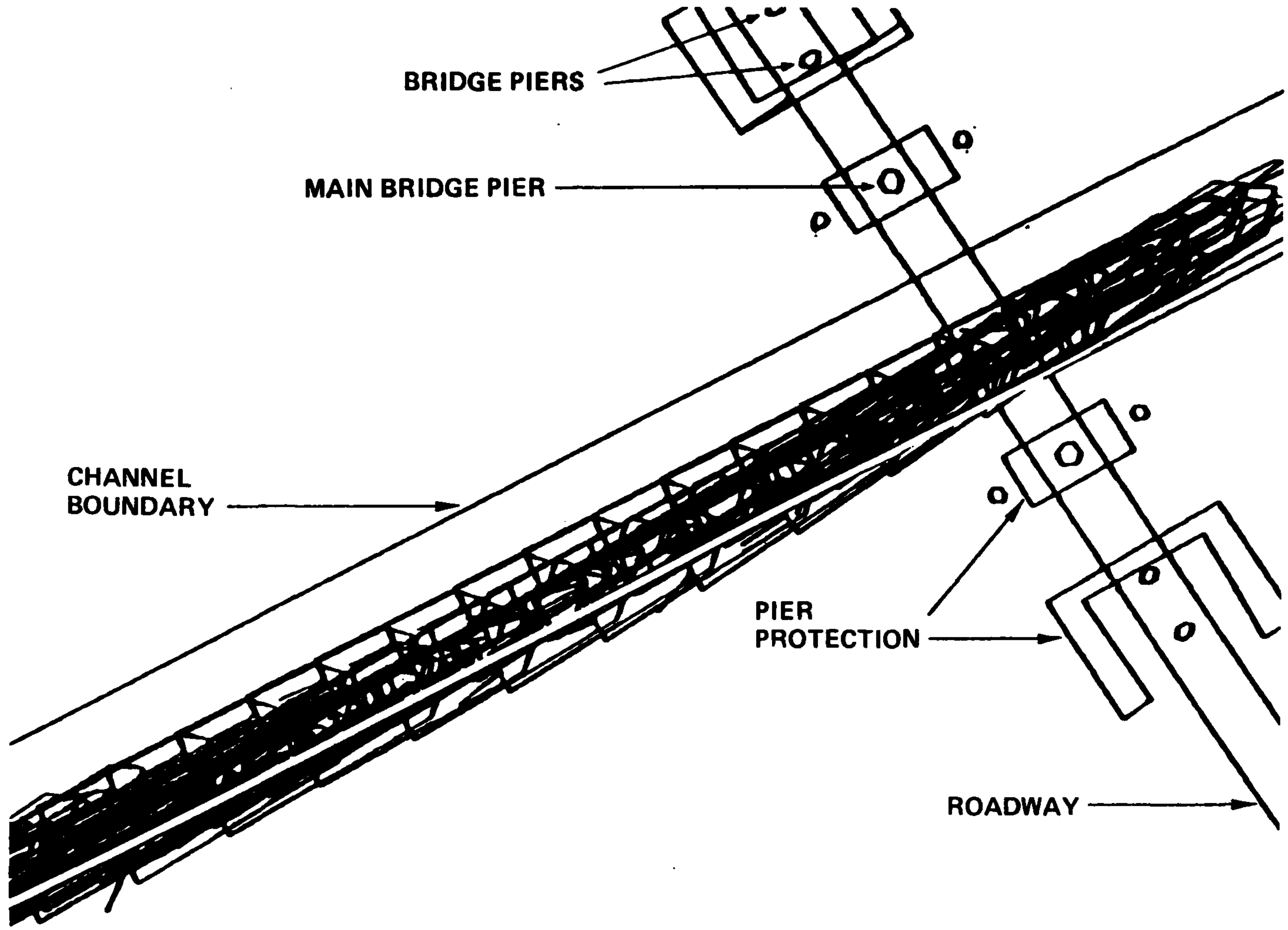


Figure 24. Composite Track Plot of Passages in Navigational System Design 2 – Fog Conditions

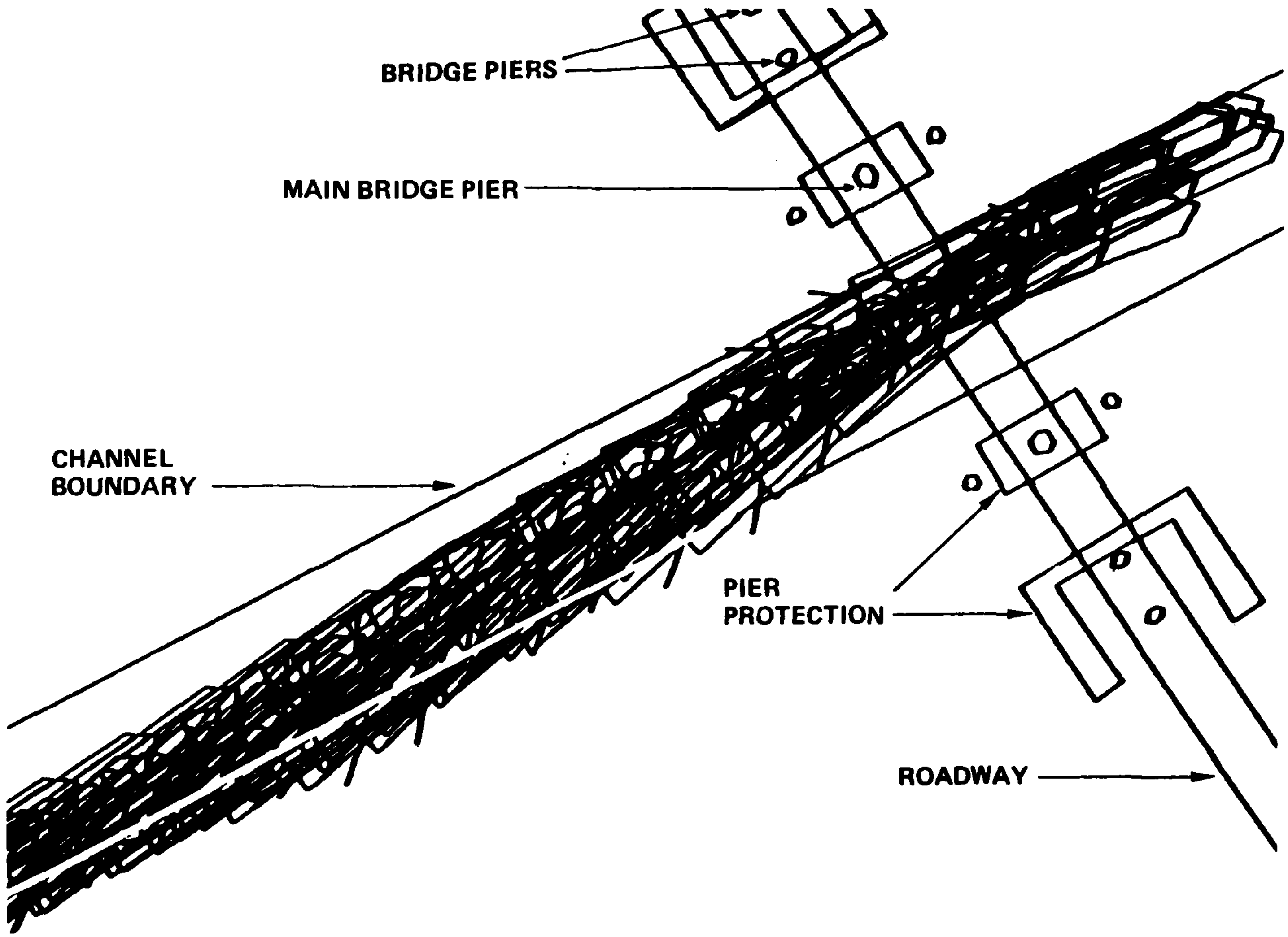


Figure 25. Composite Track Plot of Passages in Navigational System Design 3 – Thunderstorm Conditions.

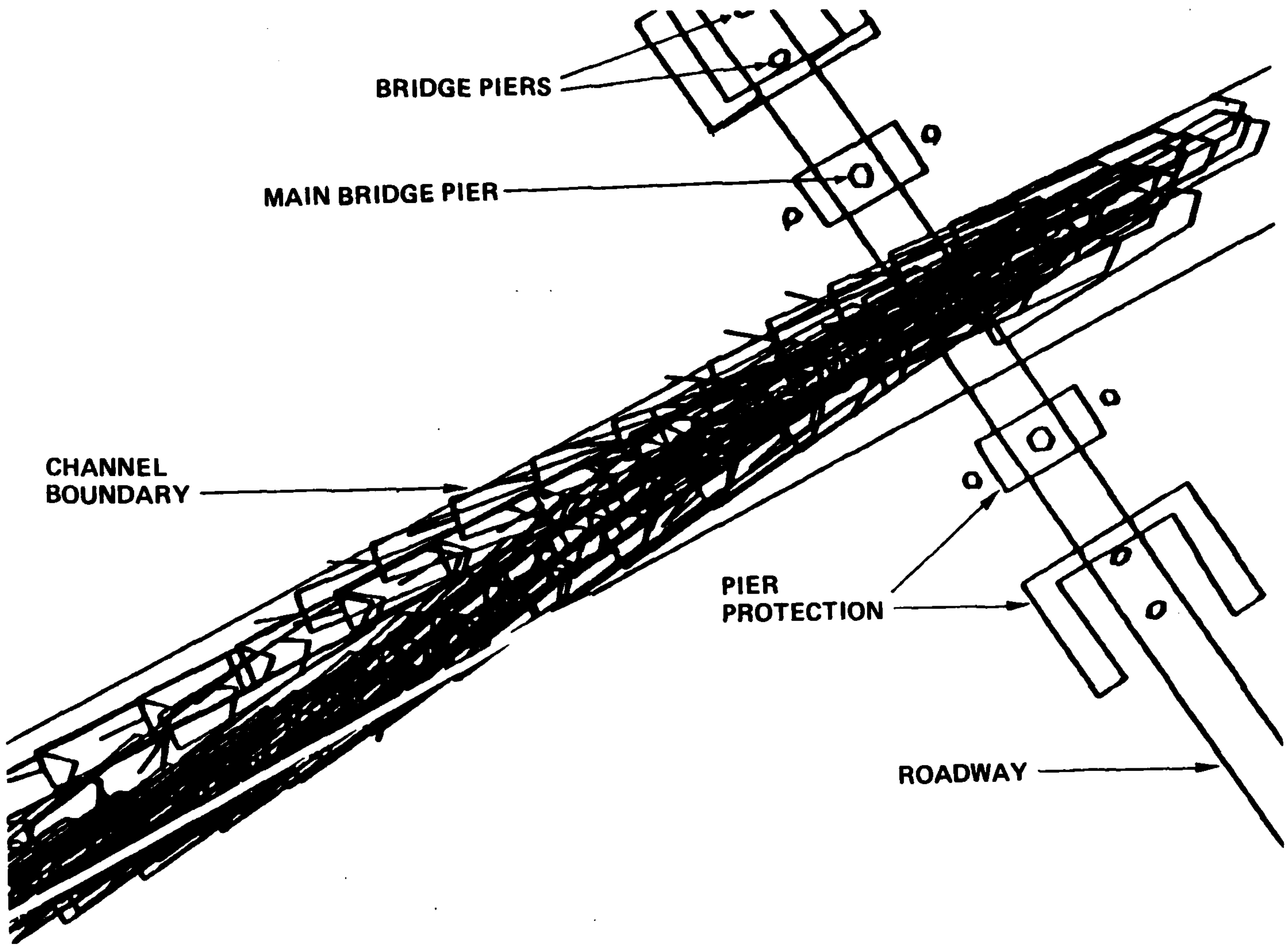


Figure 26. Composite Track Plot of Passages in Navigational System Design 3 – Fog Conditions.

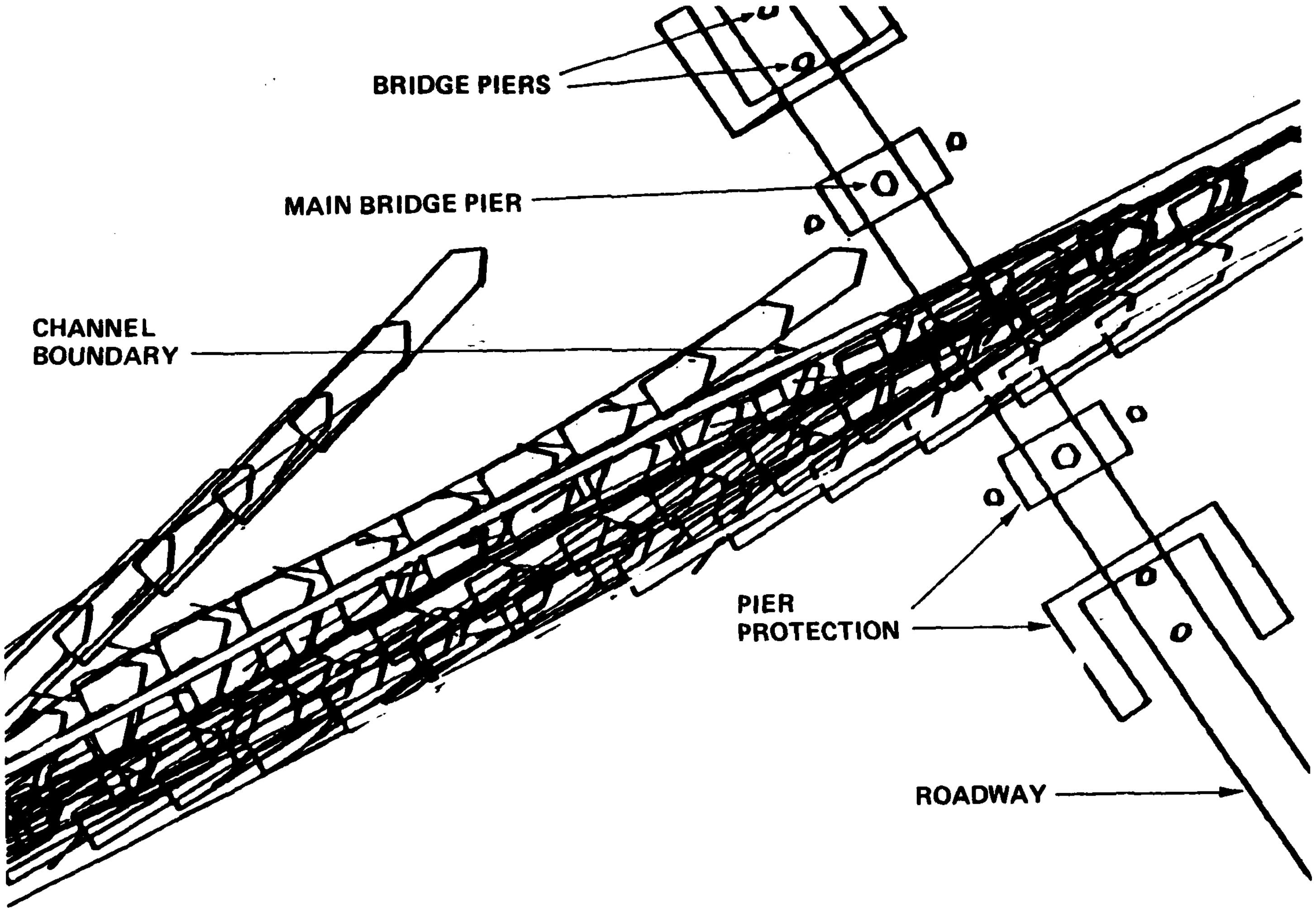


Figure 27. Composite Track Plot of Passages in Navigational System Design 4 – Thunderstorm Conditions.

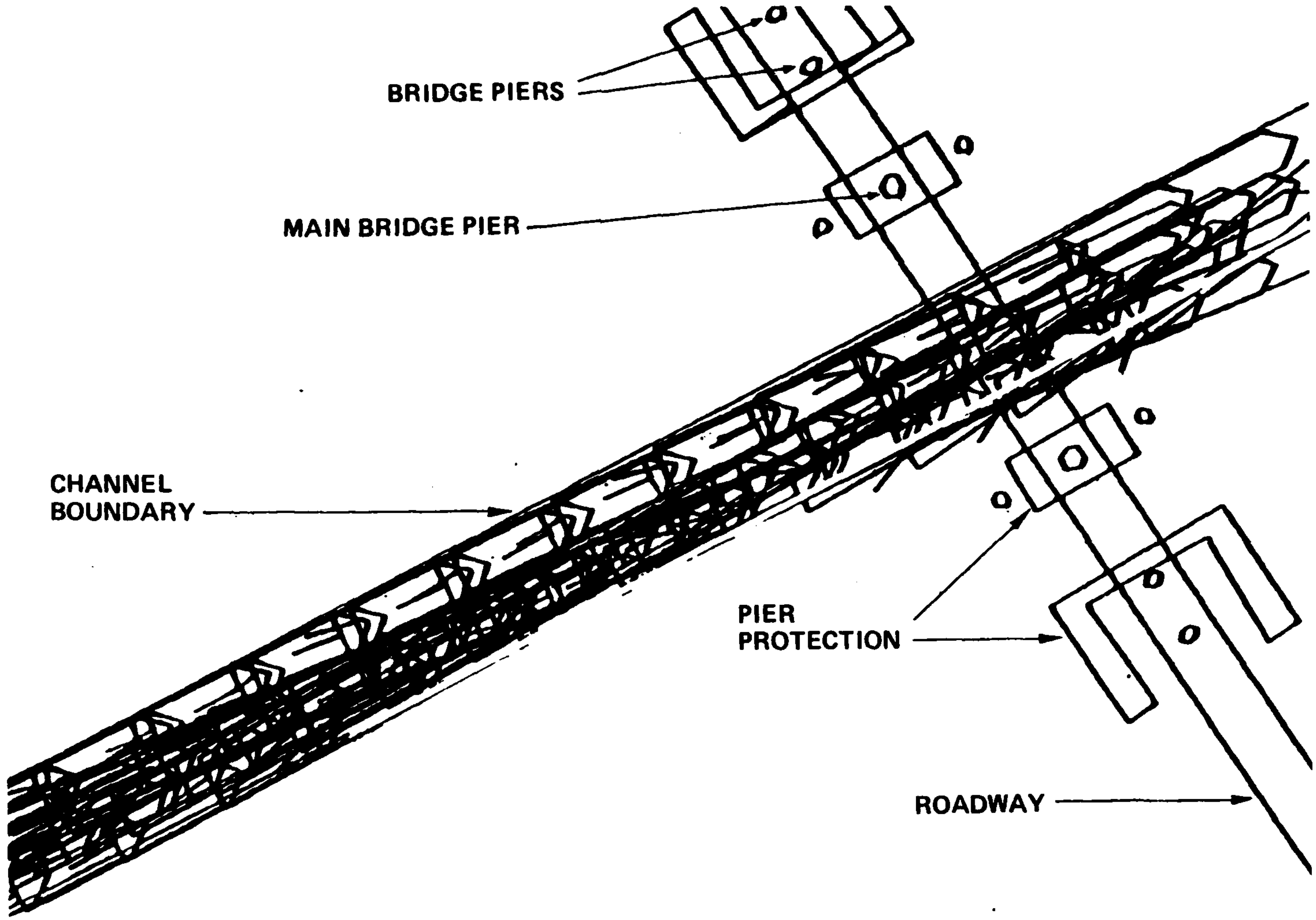


Figure 28. Composite Track Plot of Passages in Navigational System Design 4 – Fog Conditions.

TABLE 11. VESSEL PROXIMITY MEASURES ANALYSIS OF VARIANCE SUMMARY TABLE OF NAVIGATIONAL CONDITION EFFECT[a]

Dependent Variables	Navigational Condition (N)	Appendix Table
Closest Point of Approach to Bridge	4.28***	G1
Ave. Distance of Ship from Bridge	3.12**	G2
Var. of Ship's Distance from Bridge	1.47	G3

NOTES: 1. Individual ANOVA Summary Tables can be found in Appendix G according to the reference numbers listed in the Table.

2. Significance Levels: * = $p < 0.10$
** = $p < 0.05$
*** = $p < 0.01$

No * indicates no significant effect.

[a]Values reported are F ratios.

A similar pattern of results was observed for variation in vessel distances from the bridge (see Figure 31) but the differences were not statistically significant; thus it cannot be concluded that they were due to the differences among navigational system designs.

Due to the fact that some transits were terminated before the vessel had passed the bridge, there were cases in which the variability of distance from bridge could not be calculated. These missing data were estimated by means of a least-squares regression based upon data from all of the thunderstorm and fog scenarios.

Considering all these dependent variables simultaneously, it can be concluded that the precision electronic navigation aid (NSD3) provided significantly greater bridge safety in terms of proximity measures than any alternative design. Furthermore, the extended Cut A Channel design (NSD4) was found to be no more beneficial than the present channel design (NSD2). All three alternatives were found to be superior to the 1980 design under **favorable** as well as **adverse** conditions (NSD1F and NSD1A).

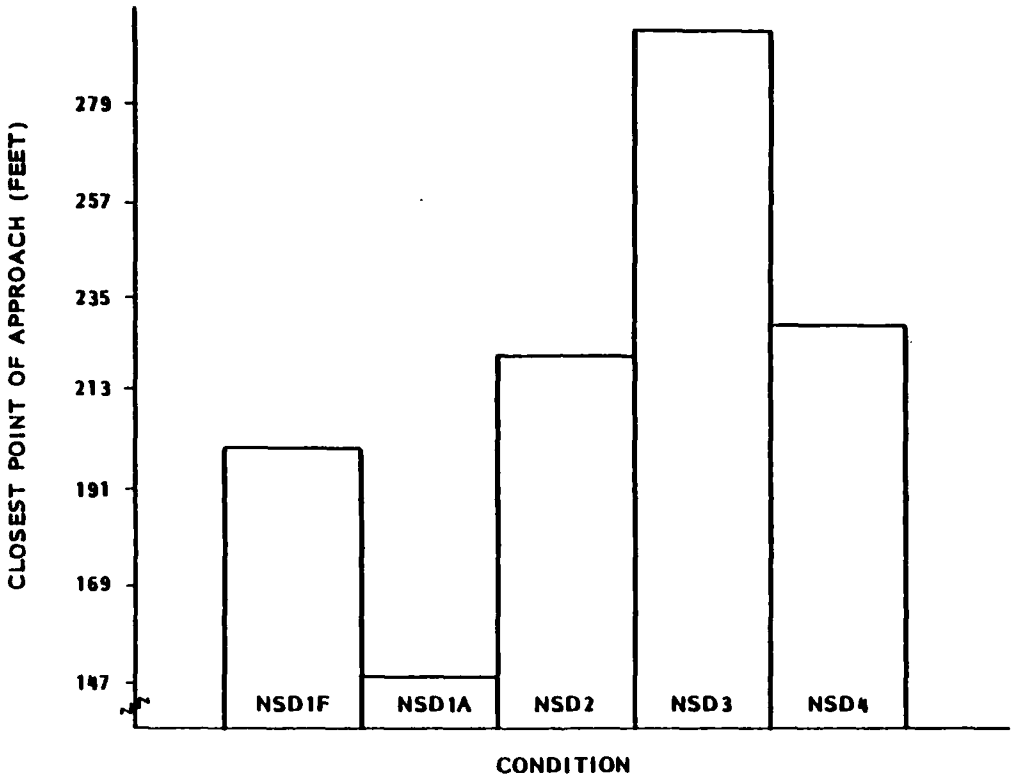
5.4 THE EFFECTS OF NAVIGATIONAL SYSTEM DESIGNS ON VESSEL CONTROLLABILITY MEASURES

The analyses of controllability measures followed the same format as the analyses of proximity measures. Four classes of controllability variables were examined. The first was yawing characteristics, including variability of heading, average yaw rate, and variability of average yaw rate. Yawing characteristics describe the vessel's horizontal oscillation around course-made-good. The second class was swept path characteristics which describe the area of the water's surface swept by the vessel's hull while transiting the waterway. Both average swept path and variability of swept path were analyzed. The third category of controllability variables described rudder control activity. Three variables were measured: the average absolute rudder angle, variability of rudder angle, and number of rudder reversals. The fourth and final category was deviation from channel centerline measures. Both average deviation from centerline and variability of deviation from centerline were examined.

It should again be emphasized that there are no absolute standards for the evaluation of vessel controllability measures. Their analysis here is to aid in the interpretation of vessel proximity analyses. Of specific interest was the determination of vessel maneuvering required to achieve the observed distances from bridge structures.

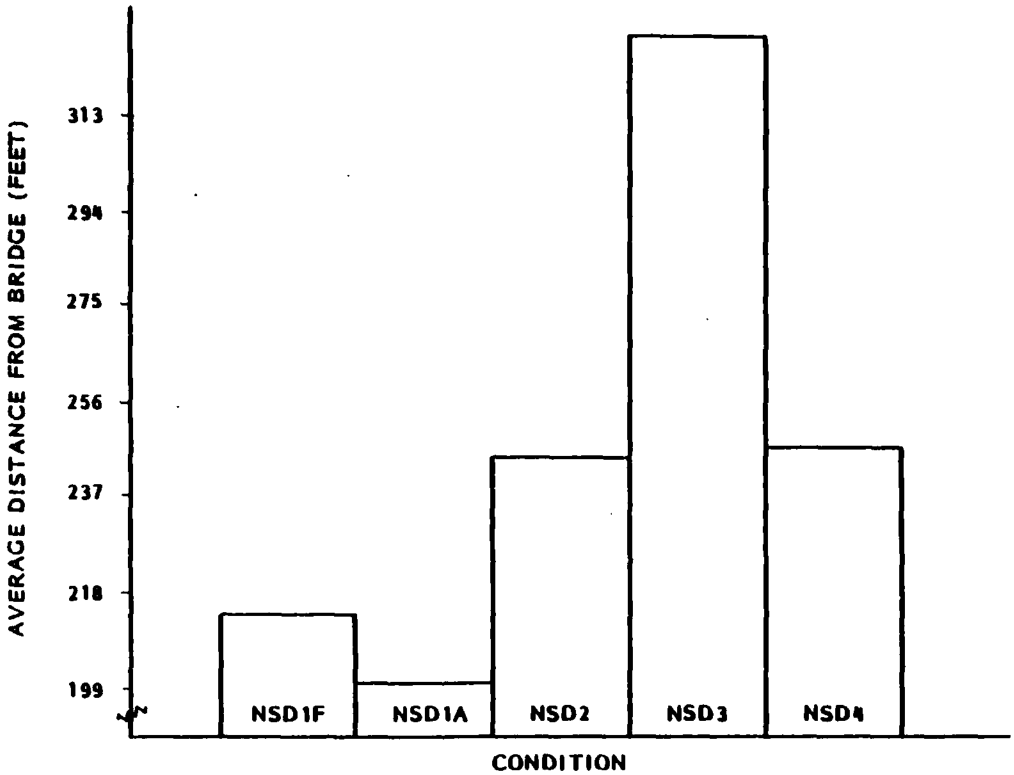
Table 12 provides the means and standard deviations for all controllability variables. These means were compared using a Single Factor Repeated Measures ANOVA. Navigational System Design was the single factor and had five levels (NSD1F, NSD1A, NSD2, NSD3, NSD4). Pilots served as the blocking variable. A total of 10 analyses were performed, one for each dependent variable, and their results are summarized in Table 13. The individual ANOVA Summary Tables for each variable are provided in Appendix H.

Variability of heading was greatest in NSD3, while little difference among the other four designs was found (See Figure 32). NSD3 was associated with an increase of 2.3 degrees variation above the next highest condition (NSD1A) and almost three degrees greater than NSD4, the lowest condition in heading variation. Again it is interesting to note the close similarity of NSD2 and NSD4, which differed by only 0.22 degrees. This indicates that the proximity of the turn to the bridge was not a major cause of heading variations within 0.5 nm of the bridge. The greater heading variation associated with use of the precision navigation system reflected greater pilot



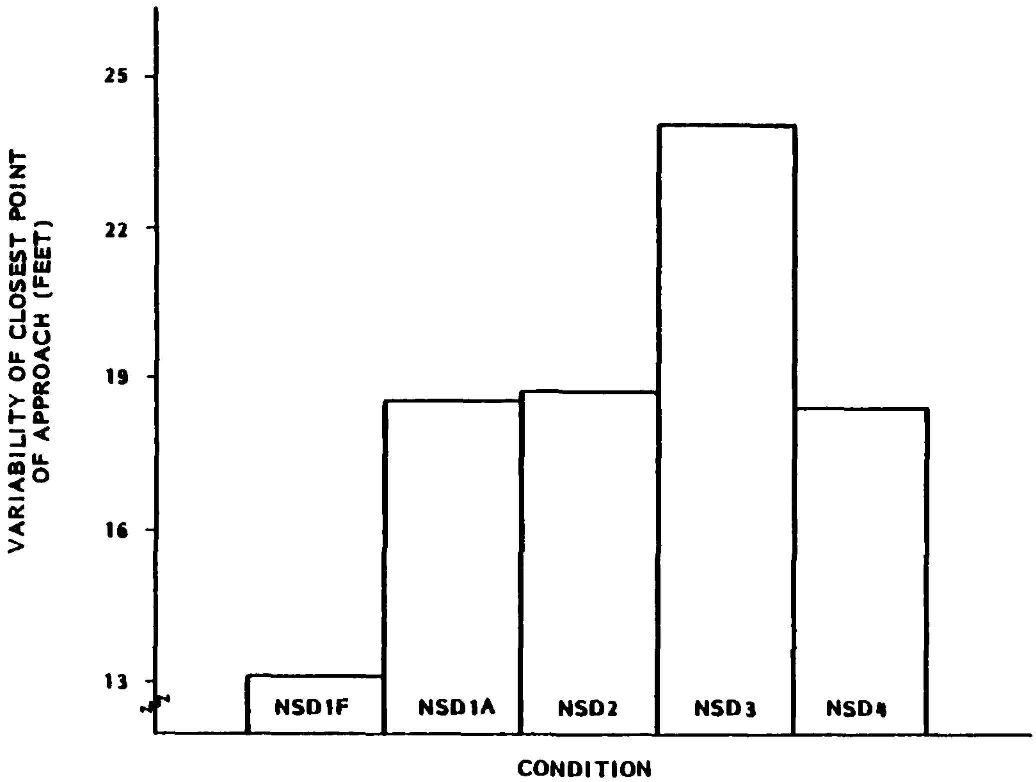
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 29. Closest Point of Approach in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSDIF). Bars Represent Mean Value for Each Condition (N = 7).



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 30. Average Distance from Bridge in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 31. Variability of Closest Point of Approach in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condtiion (N = 7).

TABLE 12. DESCRIPTIVE STATISTICS FOR CONTROLLABILITY MEASURES IN NAVIGATIONAL CONDITIONS COMPARISONS

Dependent Variable		Navigational Condition 1F	1A	2	3	4
Variation in Heading (deg.)	M	2.00	2.39	1.95	4.69	1.73
	SD	0.63	0.62	0.69	2.45	0.96
Average Absolute Rate of Turn (deg./sec.)	M	0.55	0.60	0.45	0.49	0.42
	SD	0.16	0.07	0.07	0.21	0.10
Variation in Rate of Turn (deg./sec.)	M	0.40	0.41	0.40	0.39	0.40
	SD	0.07	0.01	0.02	0.04	0.05
Average Swept Path (feet)	M	233.77	241.43	240.22	281.34	216.54
	SD	16.86	32.73	39.70	10.67	43.89
Variation in Swept Path (feet)	M	32.72	32.32	30.11	53.54	19.97
	SD	10.21	5.16	9.93	17.65	7.50
Average Absolute Rudder Angle (deg.)	M	9.99	10.71	8.78	11.90	8.31
	SD	1.96	2.85	1.86	3.36	4.95
Variation in Rudder Angle (deg.)	M	7.04	7.21	7.33	8.72	5.31
	SD	1.50	1.60	1.59	1.96	0.94
Number of Rudder Reversals	M	5.42	4.28	4.92	4.07	3.92
	SD	2.69	1.18	0.97	1.39	2.00
Average Deviation From Centerline (feet)	M	226.74	220.70	198.78	152.03	168.39
	SD	24.63	65.55	54.96	45.13	129.86
Variation in Deviation from Centerline (feet)	M	51.04	50.49	42.12	83.97	43.04
	SD	34.38	20.90	19.13	18.89	24.99

NOTE: N = 7 for each statistic.

maneuvering of his vessel which was probably the result of more certain knowledge of his position.

Marginally significant differences in average yaw rate were observed. An examination of Figure 33 reveals that these differences were small. Yaw rates were slightly greater in the 1980 designs (NSD1F and NSD1A) than in the alternative designs. This was perhaps due to the closer bridge proximity and reduced horizontal bridge clearance provided by the NSD1 conditions when compared with the others. Pilots may have attempted more rapid recovery from the turn under these conditions.

Significant differences among navigational system designs were found for both swept path variables. These differences are graphically presented in Figures 35 and 36 for average swept path and variability of swept path respectively. Note the similarity in pattern across both figures. The precision navigation aid was associated with greater swept path and greater variability of swept path. Little difference between the NSD1 conditions and NSD2 was observed. On both variables, NSD4 was the lowest. Thus with the exception of the PENA, the proximity of the turn to the bridge seemed to be the critical factor here. The swept paths in the extended Cut A Channel design (NSD4) were on

TABLE 13. VESSEL CONTROLLABILITY MEASURES ANALYSIS OF VARIANCE SUMMARY TABLE OF NAVIGATIONAL CONDITION EFFECT[a]

Dependent Variables	Navigational Condition (N)	Appendix Table
Ave. Yaw Rate	2.58*	H1
Var. of Yaw Rate	< 1	H2
Var. of Heading	6.40***	H3
Ave. Swept Path	4.88***	H4
Var. Swept Path	9.74***	H5
Ave. Rudder Angle	1.36	H6
Var. Rudder Angle	4.32***	H7
Rudder Reversals	1.38	H8
Ave. Dev. Centerline	1.23	H9
Var. Dev. Centerline	3.13**	H10

NOTES: 1. Individual ANOVA Summary Tables can be found in Appendix H according to the reference numbers listed in the Table.

2. Significance Levels: * = $p < 0.10$
** = $p < 0.05$
*** = $p < 0.01$

No * indicates no significant effect.

[a] Values reported are F ratios.

average 21 feet less than those in the conditions where the turn was closer to the bridge and no PENA was used. The variability of swept path of NSD4 averaged about 12 feet less than the same conditions. The greater values on these variables for NSD3 further provides evidence for the fact that greater maneuvering of vessels occurred when pilots had the PENA.

This pattern of results was also found for variability of rudder angle, the only rudder control variable where significant differences were observed. Differences among navigational system design means for average absolute rudder angle, variability of rudder angle, and number of rudder reversals are graphically illustrated in Figures 37, 38, and 39 respectively. NSD3 was highest in rudder angle variation (Figure 38). NSD1F and NSD1A and NSD2 were next highest and similar to each other; NSD4 was the lowest. The PENA, therefore, was again associated with increased maneuvering. With that condition aside, the proximity of the bridge to the turn was the most critical.

While differences in average absolute rudder angle were not statistically significant, it is interesting to note that the largest value was in the PENA condition. This would be consistent with the general findings of increased vessel maneuvering with the PENA.

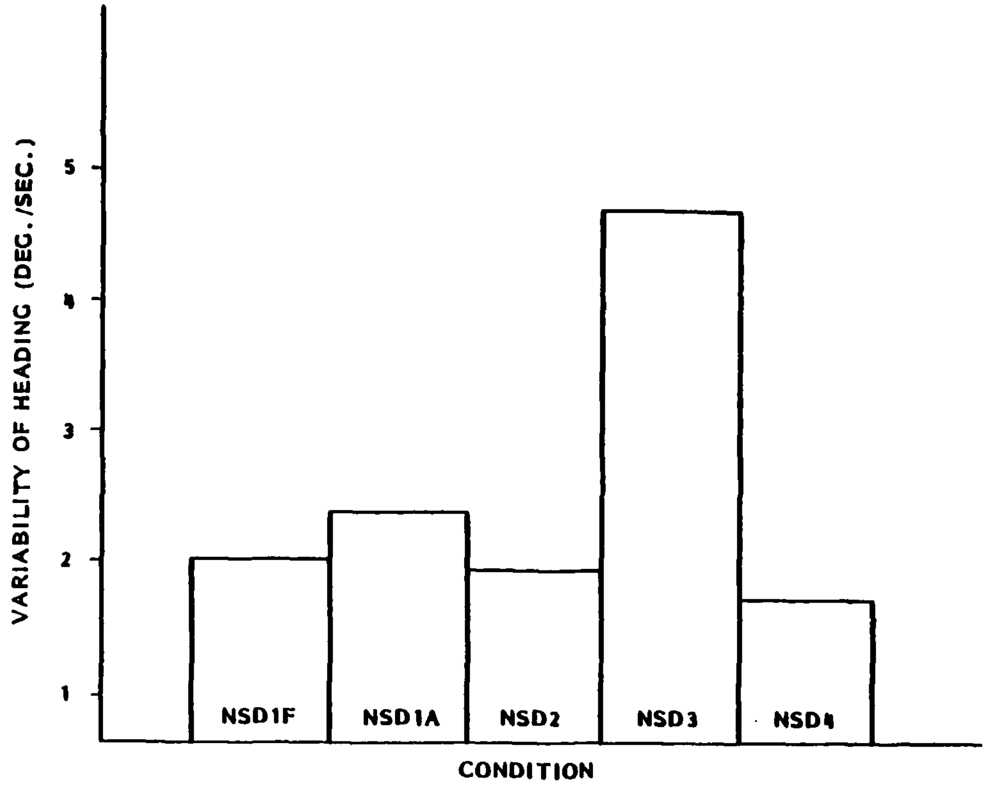
The final controllability analyses involved the distance from channel centerline measures. Average distance from centerline results are shown in Figure 40. Overall, the average distances were larger than might be expected for a vessel with a beam of 155 feet in a 500 foot wide channel. Inspection of the composite track plots (Figures 20 - 28) reveals that as vessels approached the bridge they generally maintained tracks close to, and sometimes beyond, the southern boundary of the channel. This was perhaps due to the size and difficult maneuvering characteristics of the vessel, a size with which some pilots were unfamiliar. No significant differences among conditions were found with respect to variability of distance from centerline (Figure 41). Considering the two variables simultaneously, it appears that while average distance from the channel centerline was lowest with the PENA (NSD3, see Figure 40), variation of the vessel around the centerline was greatest (see Figure 41). This would strongly suggest that the availability of specific knowledge regarding the vessel's position in the channel enabled pilots to execute greater maneuvering responses to control the vessel's position.

Integrating all controllability variables, it was observed that when using the PENA, pilots made more use of the vessel's rudder to maneuver their vessels. This resulted in greater heading variation and swept path characteristics while maintaining closer proximity to the channel's centerline. This greater maneuvering also resulted in greater CPA and average distance from bridge structures. It seems reasonable to conclude that when pilots have access to precision navigation information they use it to aid in correcting the position of the vessel with respect to the centerline as the vessel nears the bridge.

5.5 PILOT EVALUATIONS

5.5.1 General Approach

Following each individual passage, pilots were asked to complete the Pilotage Evaluation Rating Scale, a series of scales on which the passage they had just made was rated on various dimensions generally involving the transit's workload, effort and difficulty. When all their passages were completed, pilots were asked to fill out the Pilot Opinion Questionnaire. This questionnaire had an open-



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 32. Variability of Heading in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Respresent the Mean Value for Each Condition (N = 7).

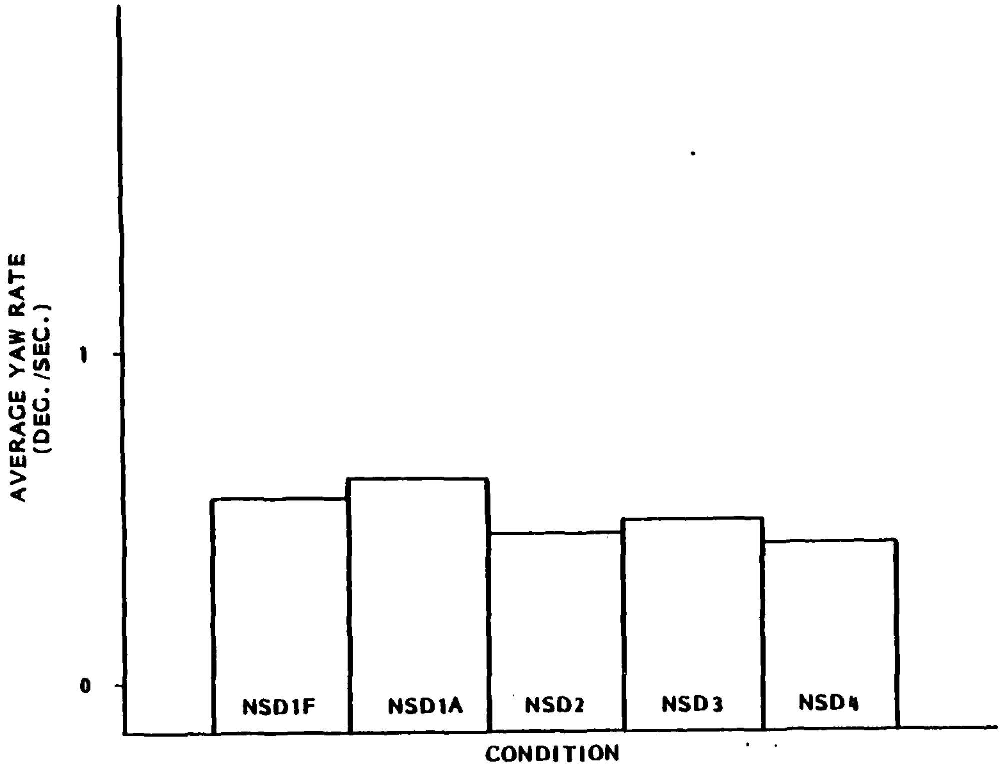


Figure 33. Average Yaw Rate in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).

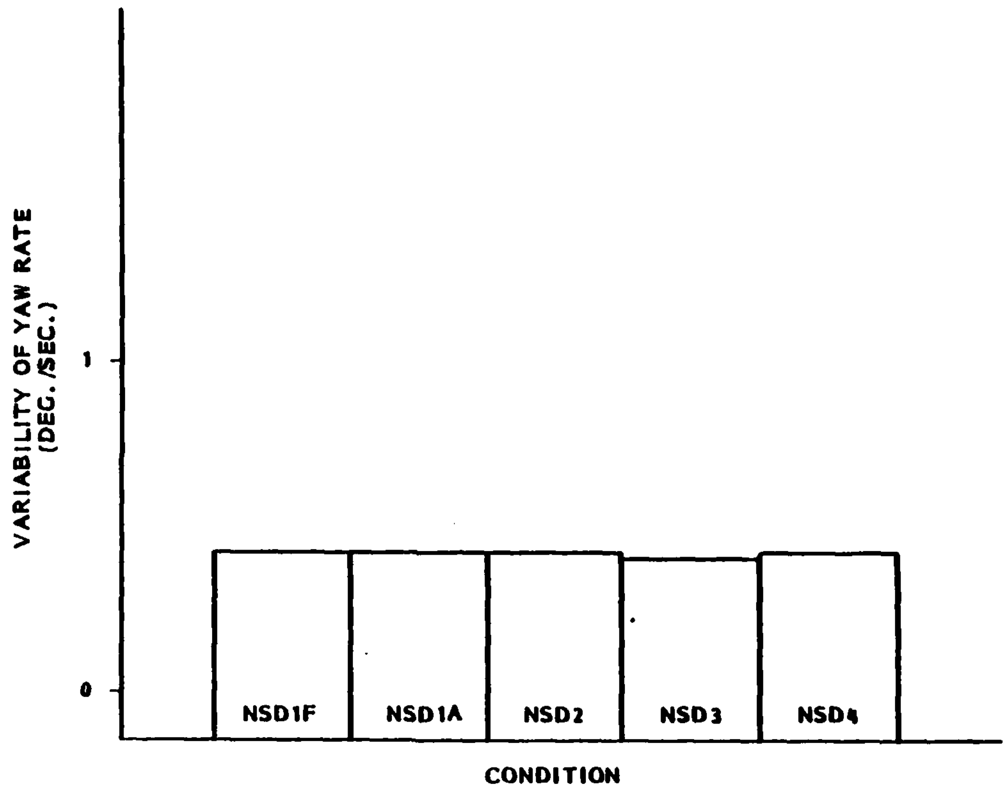
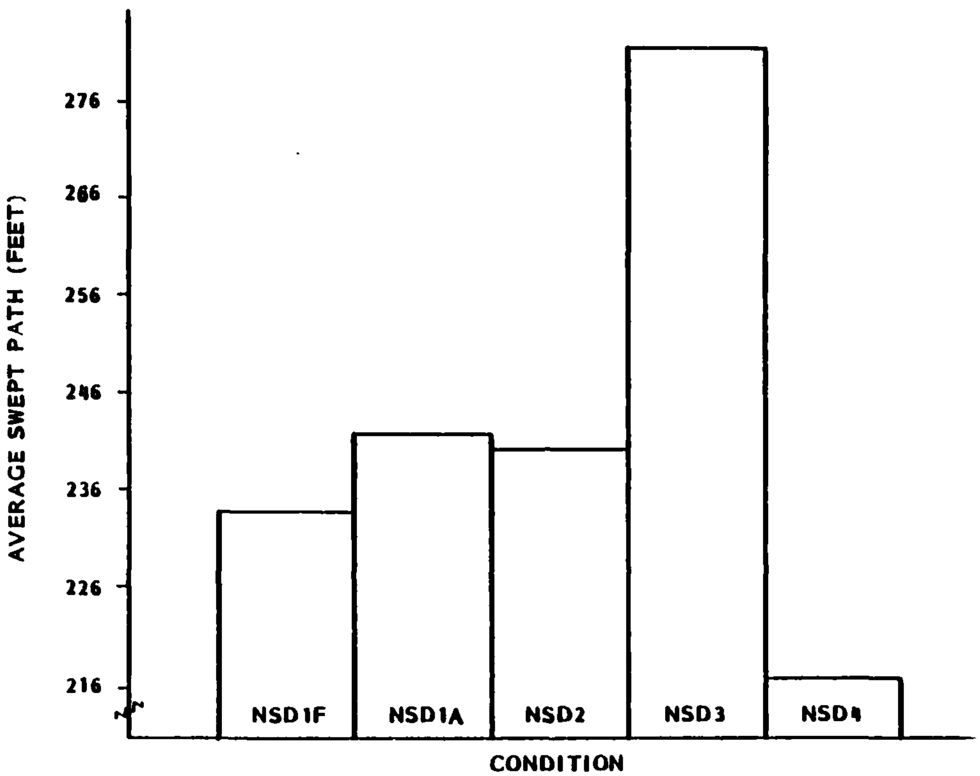
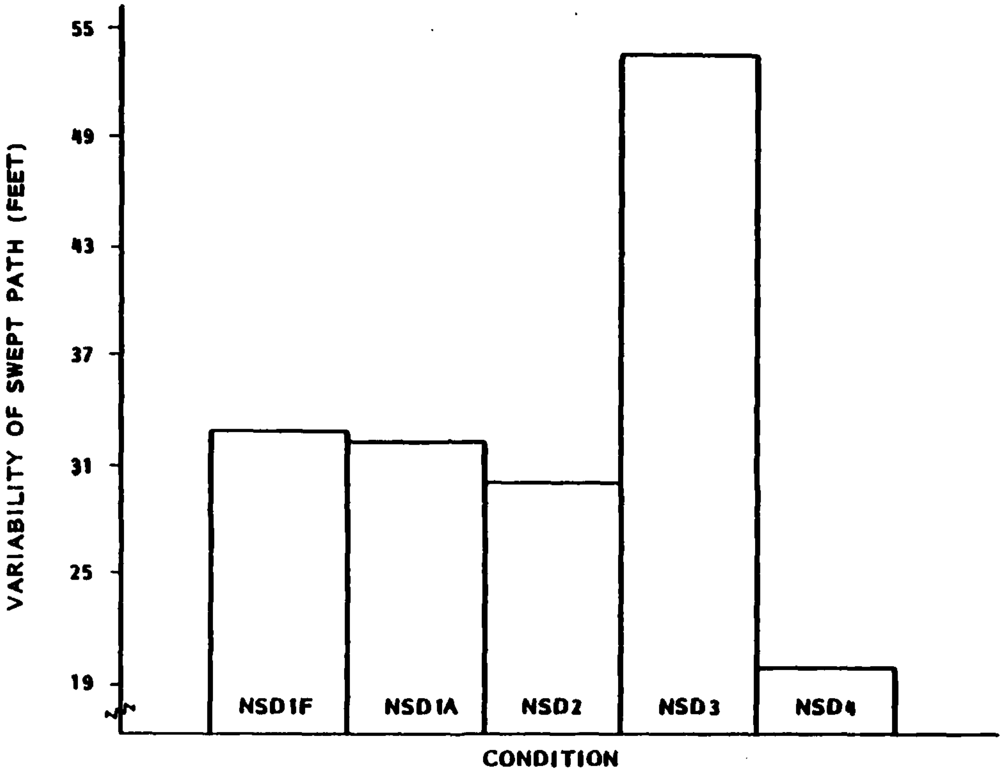


Figure 34. Variability of Yaw Rate in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).



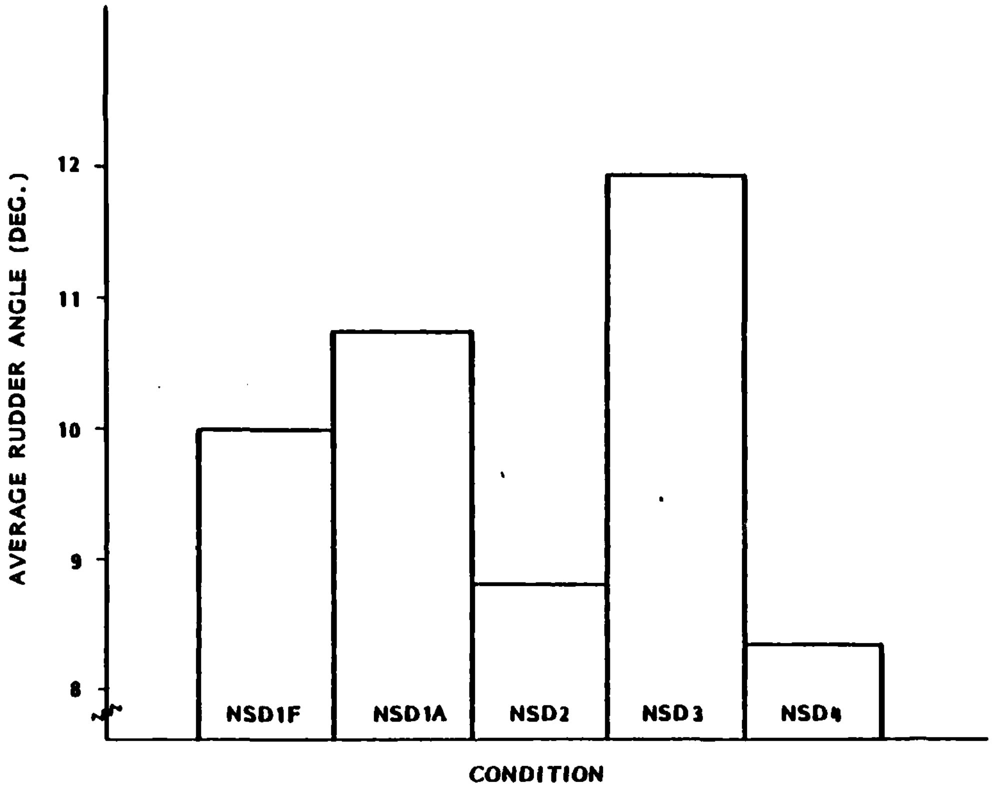
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 35. Average Swept Path in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).



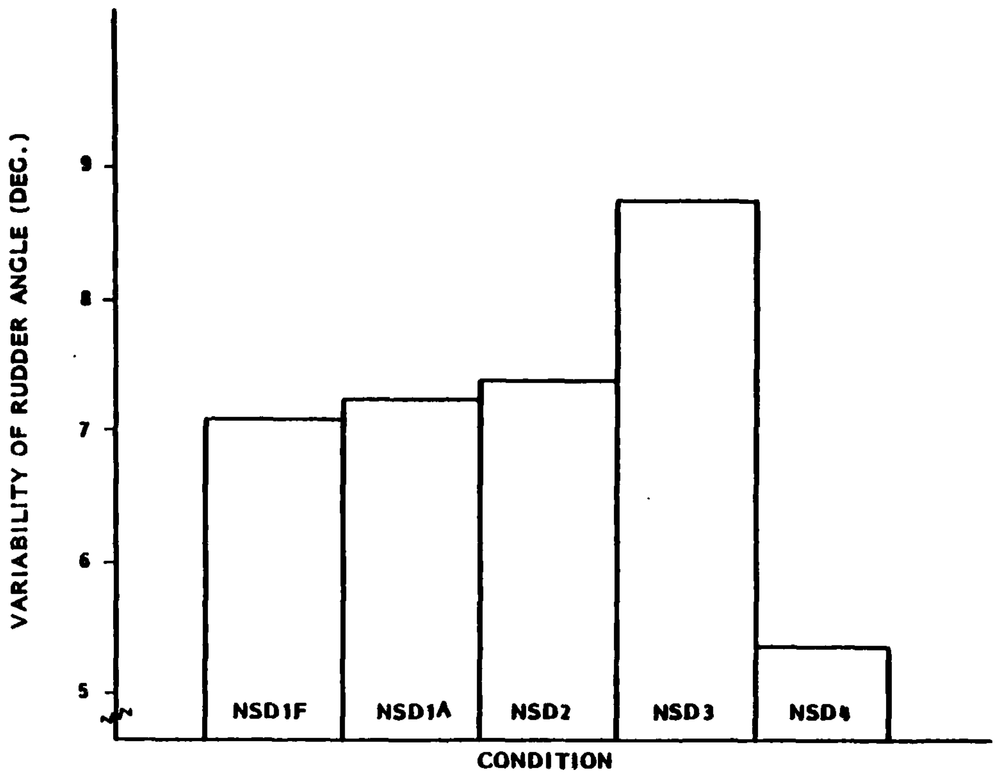
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 36. Variability of Swept Path in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).



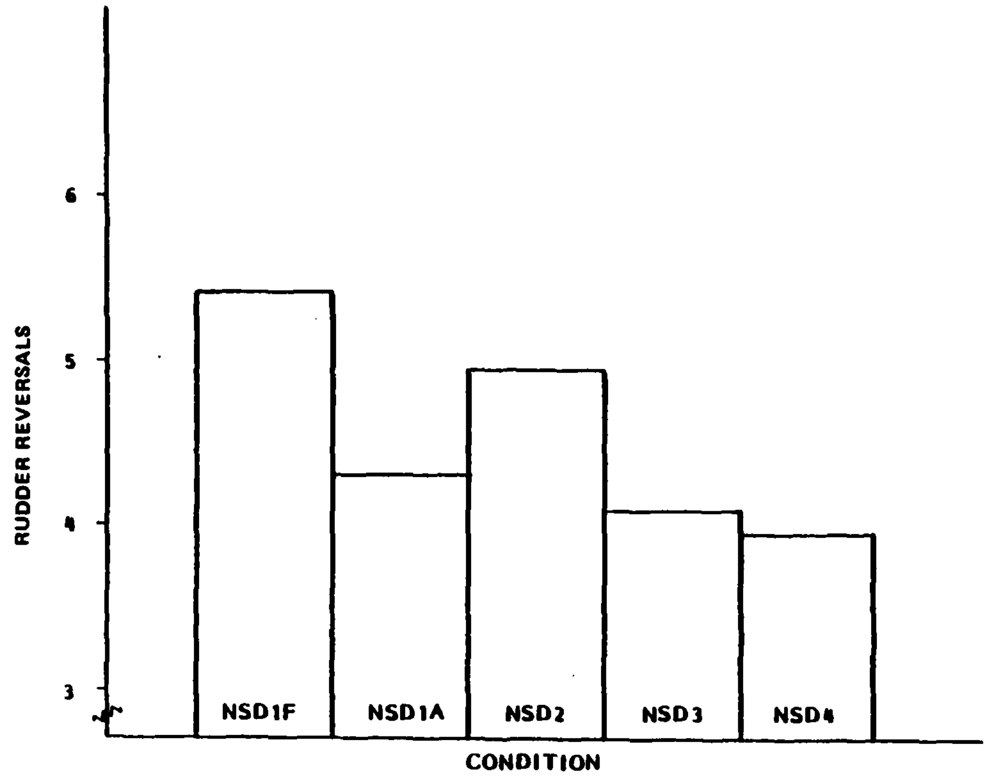
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 37. Average Rudder Angle in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).



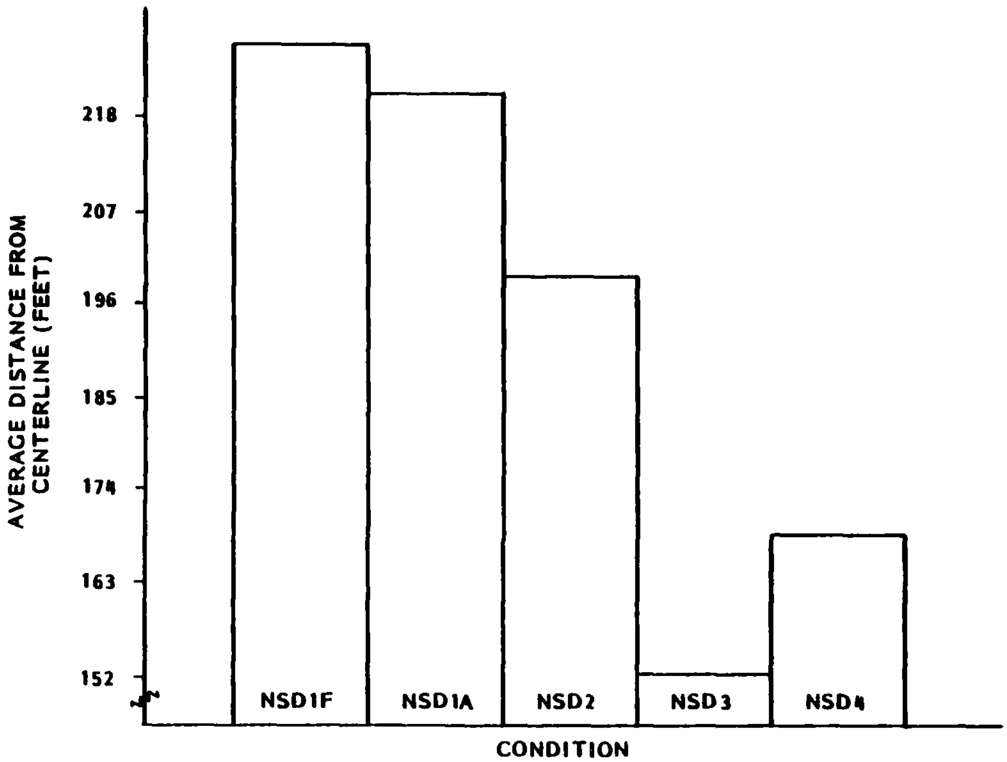
NOTE. Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 38. Variability of Rudder Angle in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).



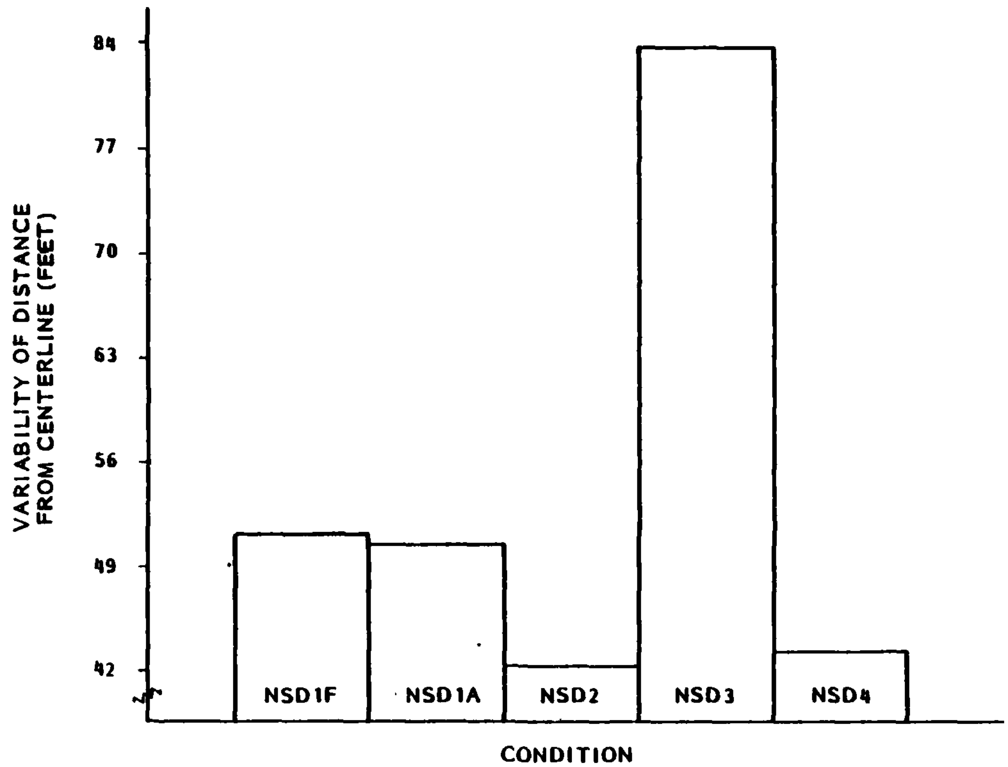
NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 39. Number of Rudder Reversals in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSDIF). Bars Represent the Mean Value for Each Condition (N = 7).



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 40. Average Distance from Centerline in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bar Represents the Mean Value for Each Condition (N = 7).



NOTE: Due to the truncation of the scale of the dependent variable, differences among the conditions and not full magnitudes are emphasized in this figure.

Figure 41. Variability of Distance from Centerline in Each of the Four Navigational System Designs Under Unfavorable Conditions and in Navigational System Design 1 Under Favorable Conditions (NSD1F). Bars Represent the Mean Value for Each Condition (N = 7).

ended format within which pilots could express their opinions on the quality of the simulation and the feasibility of the transits they made. Copies of both forms are provided in Appendix C.

The purpose of the analyses to be reported here was to incorporate pilot's subjective evaluations and opinions into the understanding of bridge passage safety derived from the analyses of vessel proximity and controllability measures. As with controllability variables, there were no absolute standards against which to compare their responses. Instead, the focus was on relative comparisons between environmental conditions and navigational system design, and a qualitative assessment of users' opinions.

5.5.2 Pilot Evaluation Rating Scale (PERS)

The PERS was made up of five scales relating to operator (pilot) evaluation of workload, cognitive load, stress level, shiphandling difficulty, and task difficulty. In addition, the scales were combined to yield a composite total workload score which was based on all of the dimensions listed above.

Descriptive statistics, means and standard deviations for each of the scales and the composite score are provided in Table 14. The data in Table 14 are organized as a function of Environmental Condition and Navigational System Design. The interpretation of the means for each variable can be made by considering (1) the possible range of values that

TABLE 14. DESCRIPTIVE STATISTICS FOR PILOTAGE EVALUATION RATING SCALES AS A FUNCTION OF ENVIRONMENTAL CONDITION AND NAVIGATIONAL SYSTEM DESIGN

		THUNDERSTORM Navigational System Design				FOG Navigational System Design			
Dependent Variable		1	2	3	4	1	2	3	4
Cognitive Load [d]	M	45.14	41.42	43.28	42.14	38.57	37.14	38.42	38.14
	SD	8.23	7.87	6.70	6.46	6.07	4.84	6.82	7.12
Stress Level [c]	M	28.42	28.00	28.00	26.85	24.42	22.57	23.42	24.00
	SD	4.31	5.25	5.25	3.71	5.56	6.75	8.73	6.83
Task Difficulty [c]	M	27.71	27.57	28.71	27.28	23.57	22.00	20.42	23.42
	SD	2.56	3.15	1.97	3.14	3.95	5.00	7.09	7.63
Shiphandling Difficulty [b]	M	20.14	19.42	21.14	18.8[illegible]	21.00	18.71	19.85	18.14
	SD	7.24	6.99	7.66	5.72	7.81	6.79	8.39	6.36
Operator Workload Evaluation [a]	M	6.42	7.00	6.71	6.71	6.28	6.14	5.71	6.00
	SD	1.81	1.41	1.79	1.25	1.38	1.21	1.97	1.73
Total Workload Score [e]	M	136.28	131.71	136.28	130.00	121.71	113.71	115.28	117.14
	SD	21.51	21.11	21.01	17.73	20.58	21.63	31.56	25.64

NOTES: 1. N = 7 for each statistic.

2. Higher values indicate greater quantities of the variable rated.

[a] Scale = 1 to 9

[b] Scale = 3 to 27

[c] Scale = 7 to 49

[d] Scale = 6 to 54

[e] Scale = 19 to 171

the variable could assume and (2) that higher values represent greater quantities of the variable for which the mean was given. Generally, lower values were associated with more favorable conditions and higher vlaues with more difficult conditions.

Tests of differences among means for each variable were made using a Two Factor Repeated Measures Analysis of Variance. The two factors were Environmental Condition (having two levels: thunderstorm and fog) and Navigational System Design (having four levels: NSD1, NSD2, NSD3, and NSD4). Pilots served as the blocking variable. Six separate ANOVAs were performed, one for each variable. The individual ANOVAs are provided in Appendix I. The results of the ANOVAs are summarized in Table 15.

As with previous analyses, no significant interactions between Navigational System Design and Environmental Condition were observed. Only one significant Navigational System Design effect was observed and that pertained to shiphandling difficulty. The pilots rated shiphandling easier in NSD4 than in the other designs. This finding may have resulted from the longer straight portion of channel before the bridge in this extended Cut A Channel condition. No significant differences between the navigational designs were observed on any of the other variables.

Environmental Condition levels were significantly different on all variables but shiphandling difficulty. In all cases, thunderstorm conditions were worse than fog conditions. That is, pilots rated the thunderstorms as requiring more cognitive effort, being more stressful and creating a more difficult task. Pilots also indicated that their workload was higher during thunderstorms and the overall composite workload score was higher for thunderstorms as compared with fog conditions.

5.5.3 The Pilot Opinion Questionnaire

As previously noted, the questionnaire was used to obtain pilot opinions on various aspects of the simulation. For the purposes of this discussion, these opinions will be grouped into four categories: (1) the overall quality of the simulation, (2) an evaluation of the precision electronic navigation aid, (3) an evaluation of the extended Cut A Channel design, and (4) comments and recommendations about cases not examined in the study.

Several questions were related to the quality of various aspects of the simulation. The majority of pilots rated the overall realism of the simulation as "very good" to "excellent". The worst rating given was "good". The pilots were asked if they thought their real world performance would differ from their performance on the simulator. This question was extremely important since, while simulator realism is an important prerequisite to valid performance, it is the high correlation between simulator and real world performance that is most critical in a study of this nature. The majority of pilots commented that they thought their performance would be the same in the real world as on the simulator. Several pilots commented, however, that handling vessels of the size modelled in this study is not typical and that such vessels would not be brought through Tampa Bay unless conditions were favorable. This is an important point to consider. While a smaller more typical vessel probably would not have changed the relative differences between the conditions studied (since the same vessel was used in all conditions), overall performance may have been better had a more typical vessel been used. The results, therefore, may be interpreted as including an added margin of safety in that they represent a near worst-case situation.

Also related to the overall quality and realism of the simulation was the degree to which pilots would feel confident in the results of the study. Six of the seven pilots indicated they would have confidence in the results of the study with regard to the usefulness of precision electronic navigation aids or the evaluation of channel design alternatives under adverse conditions. One pilot commented that "the conditions are real enough to force the pilot to use all available data and apply it quickly in order to stay 'afloat' ". Another pilot noted that "the simulations were very real and real world applications would be valid". The seventh pilot responded "no" to the question concerning confidence in the study's results, noting that the vessel was "unwieldly".

In summary, the pilots generally evaluated the simulation as realistic and felt that their real world performance (in the unlikely event, of course, that they were caught in conditions as severe as these) would be similar to that observed on the simulator.

Several questions were directed toward the pilots' evaluations of the precision electronic navigation aid modelled in the study. Only one of the seven pilots indicated that he had experience with precision navigation aids prior to participating in the study; the experience was of an experimental nature rather than a practical application. As for their experience with the aid at CAORF, all seven pilots said the precision electronic navigation aid was helpful.

Most indicated that it was most useful during periods of limited visibility and particularly during thunderstorms. All seven pilots also indicated that such an instrument would be useful to Tampa pilots. Several recommendations regarding its implementation were made:

- The instrument should function for the entire channel and not just in the bridge area.
- The equipment should not be too delicate or cumbersome (in size and set-up time).
- The aid should have high accuracy and reliability.
- The aid should include radar input to provide traffic information.

The pilots were also asked their preference for the modes in which information was presented, i.e., graphic or digital. Three pilots expressed a clear preference for the graphic display. One commented that the digital "required too much time for mental interpretations". The other four pilots preferred a combination of graphic and digital displays but two of these pilots agreed that the graphic display was more immediately useable.

Two of the questionnaire items related to the extended Cut A Channel design. The firs asked whether there was much difference between the turn from Mullet Key into Cut A Channel as it exists now and the turn as modelled in the extended Cut A Channel. Of the six pilots who responded to the question, two preferred the existing channel design, one the extended Cut A Channel design, and three felt it would not make much difference. The latter group felt there was a trade-off between the present turn, which is gentler but provides less time to adjust the vessel before the bridge, and the turn into the extended Cut A Channel, which would provide additional adjustment time but would require a much sharper turn. The pilot who preferred the extended Cut A Channel design noted that the turn would have to be made much wider than the turn as modelled on the simulator.

When asked if from a pilot's perspective they would like to see the extended Cut A Channel design implemented in Tampa Bay, only two pilots clearly endorsed the concept (again, provided that a turn widener were included).

In summary, pilots generally evaluated the precision electronic navigation aid as being useful and desirable to have in Tampa Bay. Their evaluation of the extended Cut A channel design was much less favorable, with the majority of pilots showing no preference for that alternative.

Finally, pilots were asked to offer their comments and recommendations concerning cases not examined in the simulation. The following summarizes their responses:

- "I would like to see an emergency anchorage dredged on both sides of (the) bridge so a voyage could be aborted for weather or mechanical problems".
- One pilot noted the need for "immediately putting radar reflective buoys out from the present bridge to provide definition of (the) opening until (the) new bridge is constructed".
- Several pilots expressed concerns over the safety of other vessel types in transiting the bridge area under adverse conditions. These included a 265,000 DWT vessel, a twin screw single rudder vessel, a large tug and barge combination, a vessel with less draft and more sail area, and a vessel loaded to maximum draft.

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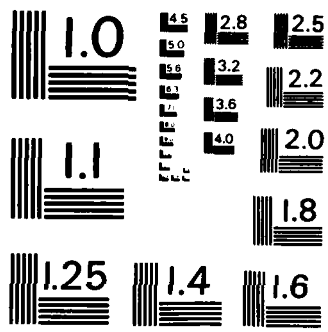

MICROCOPY RESOLUTION TEST CHART
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TABLE 15. PILOT EVALUATION RATING SCALES ANALYSIS OF VARIANCE SUMMARY TABLE OF ENVIRONMENTAL EFFECT[a]

Dependent Variable	Env. Cond. (E)	Nav. Sys. Des. (N)	Interaction (NE)	Appendix Table
Cognitive Load	20.24***	<1	<1	I1
Stress Level	23.98***	<1	<1	I2
Task Difficulty	30.34***	<1	1.04	I3
Shiphandling Difficulty	<1	3.57***	<1	I4
Operator Workload Evaluation	4.45**	<1	<1	I5
Total Workload Score	25.72***	<1	<1	I6

NOTES: 1. Individual ANOVA Summary Tables can be found in Appendix I according to the reference numbers listed in the Table.

2. Significance Levels: * = $p < 0.10$
** = $p < 0.05$
*** = $p < 0.01$

No * indicates no significant effect.

[a] Values reported are F ratios.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to determine the efficacy of alternative strategies aimed at reducing the risk of vessels colliding with the replacement Sunshine Skyway Bridge. Each of the three risk mitigation strategies considered involved a different aspect of an overall navigational system, comprising bridge characteristics, aids to navigation, and channel design. One alternative navigational system design (NSD2) involved changes in the design and position of the replacement Sunshine Skyway Bridge. This alternative has in fact been implemented in the construction plans of the new bridge. Another system design (NSD3) included a precision electronic navigation aid, while a third (NSD4) called for the seaward displacement of the turn into Cut A Channel. Conclusions regarding each of the navigational system designs are detailed below. Following the rationale outlined earlier in this report, conclusions will be drawn primarily by comparing ship-to-bridge clearances attained in the three alternative designs with those observed in baseline conditions (NSD1), the system design as it existed circa 1980, under favorable (safe) as well as unfavorable (unsafe) conditions.

Another objective of the study was to determine the effects of different forms of adverse environmental conditions on the safety of bridge passage. Both severe thunderstorms and dense fog were examined. In addition, an examination was made to determine whether bridge safety was differentially influenced by varying environmental conditions depending upon the navigational system design implemented, i.e., an interaction between environmental conditions and navigational system designs.

The conclusions from this study will be organized as follows. The effects of the environment will be discussed in the first section and then the differences between the navigational system designs will be addressed. The third and final section will offer recommendations relating to the navigational system design alternatives examined in this study.

In considering the conclusions and recommendations, the reader is urged to keep in mind that the results of the study were based upon the results obtained from a limited set of conditions. Great efforts were made to select conditions which would be most relevant to evaluation of risk mitigation strategies and permit navigation inferences to the majority of navigation scenarios in Tampa Bay. The elements of the scenarios were selected so as to approximate worst-case situations, thereby insuring that the results of the study would include increased margins of safety in more typical, less severe cases. Nevertheless, one must be cautious when making inferences to situations (scenarios) qualitatively different from those studied. For example, the control of tug and barge configurations is quite different from the control of a ship and generalizations to those situations must be made carefully. In addition, no equipment failure, crew misunderstanding, or vessel traffic were experienced by pilots during the scenarios examined. No single study can reasonably examine all possible cases and, therefore, one must exercise caution when extending the results of a study beyond its limits.

6.1 CONCLUSIONS REGARDING THE EFFECTS OF ENVIRONMENTAL CONDITIONS

With respect to the effects of the environmental conditions on bridge safety, it was concluded that the thunderstorm conditions were significantly less safe than the fog conditions. Average closest point of approach (CPA) was almost 50 feet closer to the bridge in thunderstorm conditions when compared with fog conditions. In fact, all three bridge contacts which occurred in the study happened during thunderstorm conditions. The same pattern held for average distance from the bridge although the difference was not statistically significant. In addition to vessel's closer proximity to the bridge, thunderstorms produced almost twice as much variability in each vessel transit past the bridge indicating less stable, and less safe, vessel performance. During thunderstorms, therefore, vessels were coming significantly closer to the bridge with significantly greater variability. This pattern was observed for each navigation system design hence there were no significant interactions between environmental conditions and navigation system designs.

The decrease in bridge safety with thunderstorm conditions can be understood by considering the pilot's difficult task in navigating his vessel under such extreme environmental conditions. In addition to losing nearly all visibility (which occurred in fog conditions as well), the radar presentation was severely cluttered and the vessel was subjected to strong and variable winds. The loss of radar presentation was significant since without it nearly all information which would enable the pilot to fix his position was lost. In an intense fog condition, the loss of visual contact with aids to navigation and bridge structures was partially offset by the availability of radar contact with such objects. Information existed, therefore, with which to determine the monitor vessel position. In an intense thunderstorm, the pilot was essentially blind to any aids to accurate positioning and had to estimate his position based upon the vessel's last known position, current heading and speed, estimate of distance travelled, and infrequent reports from lookouts (whose vision extended only .1 nm beyond the vessel).

Adding to the difficulty of controlling the vessel were strong and variable winds, the effects of which had to be gauged by the pilots in the absence of any visual cues to the vessel's motion. Furthermore, in several of the scenarios examined, the pilot was required to make a turn maneuver less than one nautical mile from the bridge (from Mullet Key Channel into Cut A Channel).

Given the conditions of (1) lack of accurate positioning data, (2) perturbating wind forces, and (3) turning maneuver requirements, vessel piloting was extremely difficult. The Tampa Bay pilots in this study demonstrated tremendous resourcefulness in successfully making 86 percent of their transits under these conditions (without a precision navigation aid) with the added handicaps of an extremely large and unfamiliar vessel and varying models of Tampa Bay in which to navigate.

While in the real-world, transits in such conditions would never intentionally be attempted: severe thunderstorm conditions (which in the past have proved problematic) were modelled in this study in order to test worse-case risks to bridge safety.

6.2 CONCLUSIONS REGARDING THE NAVIGATIONAL SYSTEM DESIGNS

The primary method of evaluating the relative safety of the various navigational system designs was to compare them with respect to measures of vessel proximity to bridge structures. These measures of proximity were examined: closest point of approach (CPA) to bridge, average distance of vessel from bridge, and variation of average distance from bridge. The navigational system designs were found to significantly differ with respect to the first two of these three variables.

Navigational System Design 3, which incorporated the precision electronic navigation aid, produced larger values for both CPA and average distance than any other design. Generally, NSD2 and NSD4 were found not to differ significantly on these variables. When the precision navigation aid was used, CPA's averaged almost 78 feet larger than in the other two alternatives and the average distance from the bridge was approximately 80 feet greater. Interestingly, all three alternatives under adverse conditions were superior to NSD1 (the 1980 design) under **favorable** conditions. Hence all three alternative designs resulted in increased bridge safety.

Based upon these findings, it can be concluded that the design incorporating the precision navigation aid provided for the greatest degree of bridge safety of the designs examined in this study. Comparing all designs simultaneously, it can be concluded that the relocation and redesign (greater horizontal clearance) of the Sunshine Skyway Bridge will result in greater bridge safety when compared with the 1980 design (NSD2 under adverse conditions was superior to NSD1 under favorable conditions). Including a precision navigation system along with the relocation and redesign of the bridge provides even greater bridge safety (NSD3 was superior to NSD2). Note that the only difference between NSD2 and NSD3 was the availability of precision navigation information in the latter.

It can be further concluded that, under the conditions studied, the extended Cut A Channel design (NSD4) provided no added margin of safety beyond the bridge relocation and redesign. The only difference between NSD2 and NSD4 was the location of the turn into Cut A Channel relative to the bridge. In the evaluation of proximity variables, NSD2 and NSD4 differed little. Hence, the relocation of the turn was not found to add to bridge safety. In fact, the only two bridge contacts which occurred in the alternative navigational system design occurred in the extended Cut A Channel design, where the entire portion of the transit under thunderstorm conditions was after the turn. Several pilots commented that in the absence of visual cues they preferred to make a turning maneuver when the wind was affecting the vessel rather than attempting to maintain a perfectly straight course. They indicated that the presence of the turn aided them in position estimation, whereas without the turn similar "sense of position" information was lacking.

The superiority of the precision navigation aid design can be attributed to the finding that the position information provided by the aid enabled the pilots to engage in increased vessel maneuvering in an effort to safely transit the bridge. The increase in piloted maneuvering of vessels with precision navigation information observed in this study is consistent with other studies of such aids available in the literature and discussed in Paragraph 2.2.5 Precision Electronic Navigation Aids.

In addition to the objective evidence for increased bridge safety with the PENA, pilots' subjective evaluations of the aid were very positive. All seven pilots in the study indicated that it would be a useful aid to decision making in Tampa Bay especially during periods of limited visibility.

6.3 RECOMMENDATIONS

Based upon the results of this study and discussions with Tampa Bay pilots who participated in the simulation, the following recommendations are offered.

Recommendation 1

The development and implementation of a precision electronic navigation aid for the pilotage of vessels in Tampa Bay should be supported. The findings of this study provided scientific evidence of increased safety of the replacement Sunshine Skyway Bridge when such an aid was used by Tampa Bay pilots to make simulated bridge passages under extremly adverse weather conditions.

The United States Coast Guard and the Tampa Bay pilots are the key figures in the eventual success or failure of such an aid. The safe navigation of U.S. waters is primarily the responsibility of the United States Coast Guard (USCG). The USCG has been a leading agency in the research and development of precision electronic navigation aids. The USCG, therefore, should be instrumental in the ultimate implementation of the aid system for Tampa Bay.

The Tampa Bay pilots will be the users of the aid. It must be developed, therefore, to be compatible with their operations. The most accurate and reliable navigation system possible would be of little value if it were not easily used by the pilots. Accuracy is only a prerequisite to the navigation aid's ultimate function which is to provide information to the mariner. If accurate information is not given in a form easily assimilated, then the value of the aid will be compromised. The aid should also be "weather-proof". Since its primary value will be during times of adverse environmental conditions, when navigational information from other sources is diminished, the aid would be of little value if it did not function under severe weather conditions. The Tampa Bay pilots have gone on record here and elsewhere providing criteria which they conclude a precision navigation aid should meet. Their comments should be carefully considered if the aid eventually developed for Tampa Bay is to be a useful aid to the mariner's decision making process.

Recommendation 2

The development and implementation of plans to extend Cut A Channel seaward, in an effort to move the turn further away from the new Sunshine Skyway Bridge, should not be supported. The results of this study provide no evidence of increased bridge safety as a result of movement of the turn.

Even though this design was found to be safer than the 1980 design, the safety of the extended Cut A Channel design did not significantly differ from that provided by the relocation and redesign of the replacement bridge alone. Furthermore, it was found not to be as safe as the design including the precision electronic navigation aid. Further development of plans to extend Cut A Channel, therefore, would not seem warranted.

Recommendation 3

Based upon discussions with the Tampa Bay pilots who participated in the study concerning vessel transportation needs in the vicinity of the bridge, it is recommended that additional consideration be given to the creation of anchorage areas in the vicinity of the bridge. At present, deep draft vessels must hold up in the channel, or in some cases proceed, when problems such as equipment failures and adverse weather occur in the immediate vicinity of the bridge. Such situations are potentially dangerous since such vessels may interfere with other traffic in the area thus increasing the chances of collision situations. Any threat situation such as this can also create potential risks to the Sunshine Skyway Bridge. While a deep draft vessel may ground before reaching the pier protection system or other bridge structures, a lesser draft vessel may not if collision avoidance maneuvers force the vessel from the channel.

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APPENDIX A

DESCRIPTION OF THE COMPUTER AIDED OPERATIONS RESEARCH FACILITY (CAORF)

The Computer Aided Operations Research Facility (CAORF), located on the grounds of the United States Merchant Marine Academy, Kings Point, New York, contains a sophisticated ship maneuvering simulator and has been operated by the U.S. Maritime Administration since 1975 for controlled research into man/ship/environment problems. Its main focus is not only to provide a simulation of the bridge environment and modelling of ship response, but also to investigate how these factors interact with and influence the shiphandler's ability to maneuver vessels under various conditions.

The emphasis on the "man-in-the-loop" affords a well rounded approach, the purpose of which is to examine the human element in marine operations.

Research conducted at CAORF is sponsored by either MARAD or clients which represent industry or other government agencies. MARAD sponsored projects typically address research questions relevant to a wide sector of the maritime industry. After a specific research question is identified, preliminary analysis is then made by marine research specialists at CAORF to determine whether CAORF on-line or off-line analysis is required. Based on these findings, a research plan and detailed experimental design may be implemented and executed, the results of which are freely publicized. A similar process is used with other clients. In this case the client and CAORF staff draw up a specific statement of objectives that define the research plan. Next, a specific program may be implemented, including the following tasks:

Experimental Design - definition of variables of interest, performance measures, requirements for data analysis.

Planning and Preparation - development of scenarios, specification of types of ships, speeds, courses and initial positions of ships in the scenarios, collection of pertinent data.

Data Base Construction - generation of visual, radar, situation display, and depth/current/bank data bases.

Test Subject Acquisition - acquisition and scheduling of practicing deck officers (master, mates, pilots).

Conduct of experiment - collection of data from on-line and/or off-line simulation.

Data Analysis - analysis of the experimental data (plots, recorded parameter values, videotape, audio, observational).

Report Preparation - presentation of results, findings/recommendations in final report form.

In addition to the brief overview of the research process at CAORF, it should be noted that CAORF has the capability to simulate any vessel in any port or area in the world.

Following is a detailed description of the major subsystems which comprise CAORF.

ON-LINE SYSTEM HARDWARE

Computerized Image Generator - Constructs the computer generated visual images of the surrounding environment.

- Images in full color, are projected onto a cylindrical screen, having a 29' radius subtending a 240° horizontal and 24° vertical field of view.
- Shading can be varied, as can illumination from full daylight to moonless night.
- Visibility in the day or night scenarios may also be reduced to simulate any degree of fog or haze.
- Gaming area extends to 50 by 100 miles.
- Visual scene updates 30 times per second to ensure smooth visual scene motion.
- Perspective is set for the actual bridge height above the waterline of the simulated vessel.

- Subjective motion information is available, but there is no capacity for physical motion simulation at this time.

- Six dynamic traffic ships are available in the visual scene. Numerous stationary ships are also available.

Wheelhouse - A simulated wheelhouse, 20' (6.1 m) wide by 14' (4.3 m) deep which contains all equipment and controls normally available on a merchant vessel.

- The equipment responds with realistic accuracy, providing a test subject watch officer the opportunity to maneuver ownship through a scenario.

- Port and starboard bridge wings, each equipped with pelorus to allow visual bearings to be taken and plotted on a chart.

- Removable tugboat control console.

- The equipment on the bridge, which can be reconfigured for single or twin screw operation, includes:

1. **Steering Controls and Displays**

- A gyropilot helm unit with standard steering modes, rate of turn indicator, rudder angle/rudder order indicators and gyro repeaters.

2. **Propulsion Control and Display**

- An engine control panel containing an rpm indicator, a combined engine room order telegraph/throttle and an operator mode switch (selection of warm-up, maneuvering and sea speeds).

- Propulsion control is possible from either the bridge or engine room.

3. **Thruster Controls and Displays**

- Bow and stern thrusters and their respective indicators and status lights.

4. **Navigation Systems**

- Two collision avoidance systems.

- Two radars capable of relative and true motion presentations.

- Digital fathometer.

- LORAN C

- OMEGA

5. **Communications**

- VHF/SSB radio.

- Docking loudspeaker (talkback system).

- Ship's whistle and sound powered phones.

6. **Wind Indicators**

- Indicate direction and true speed of simulated wind.

7. **Doppler Speed Display**

- Indicates bow and port and starboard motions.

- Indicates fore and aft motions.

Central Data Processor - Computes motion of ownship in accordance with its characteristics and under the environmental conditions.

- Models the behavior of all other traffic ships.

- Drives the appropriate bridge indicators (wind, radar, doppler, etc.).

- Communicates with and controls visual, radar, and situation display subsystems.

- Drives control station indicators.

Radar Signal Generator - Synthesizes real-time realistic video signals to stimulate 2 PPI's.

- Gaming area extends to 150 by 200 miles.

- Displays up to 40 moving traffic ships.

Control Station - Central location from which the simulator experiment is executed, monitored, and controlled.

- Traffic ships, tugboats environmental conditions and mechanical failures can be controlled by operators observing the experiment underway.

- All communications with bridge are carried out from here.

Assist Tug Simulation - Simulation of up to six assist tugs for use at any point along ownship's hull.

Human Factors Station - Remote location for observation of simulator research in progress.

- Unobtrusive observation and data gathering by experimental psychologists may be carried out here.

- Capabilities for video and audio recordings of activities of bridge personnel for playback/evaluation.

OFF-LINE SYSTEM HARDWARE

Fast-Time Simulation - In addition to "real-time" simulation, CAORF has the capability to perform off-line simulation runs independent of visual displays, wheelhouse, radar or control station.

- One-ship fast-time routine

- Two-ship fast-time routine

- Fast-time interactive steering system which allows the user to control all steering from a CRT.

Specific features of these systems are outlined under the section on "Capabilities of CAORF Apparatus".

CAPABILITIES OF CAORF APPARATUS

ON-LINE CAPABILITIES

Visual Display

- Geographical features, man-made structures and aids to navigation may be represented in both day and night scenarios under various levels of visibility in full color.

- Up to six controllable ships may be represented in the display at one time.

Ownship Simulation

- CAORF has the capability to simulate any ship model.

- Models are validated by comparing simulated maneuvers (zigzag, turning circles, spirals, crash stop and acceleration tests) with available sea trial data and/or model test data.

- Equations of motion are developed by changing coefficients such as propulsion, thruster, rudder, inertial hydrodynamics, etc.

- The types of ships that are currently available at CAORF are listed in Table 1.

Assist Tug Simulation

- Tug is a 360° rotatable Kort nozzle type, 128 DWT, length 65', beam 26', draft 9'.

- Tug has 1000 to 6000 B.H.P. available and maximum bollard pull is approximately 290,000 lbs for multiple tugs.

- All tug motion is controlled from the control station which contains six separate tug control panels.

- Other types of assist tugs are available, as tugs are simply represented by a vector specifying the magnitude and direction of forces from tugs of numerous sizes and horsepower.

- Panels indicate whether tug is active or inactive, the mode of operation (tow/push/lash), instantaneous force, rpm and direction (angle to ownship of tugboat thrust).

- Relative position of ownship and arrangement of tugs may be represented on a situation display both on the bridge and at the control station.

- Situation display has three options available:

1. Ownship outline only, no tug graphics

2. Ownship outline with tugs, no force vectors

3. Ownship outline with tugs and force vectors

Radar and Collision Avoidance Equipment

- Navigation aids, ships, shorelines and various topographical features may be displayed, synchronized with the visual scene.

- Up to 40 moving ships can also be displayed on the radar and CAS equipment.

- Special effects include sea clutter, range attenuation, shadowing, rain clutter, noise, earth curvature effect and far shore enhancement effect.

Geographical Data Bases

- Restricted waterways and open sea channel designs have been simulated at CAORF. Some of these data bases are:

1. Valdez, Alaska
2. Santa Barbara Channel, California
3. Santa Cruz Channel, California
4. Ambrose Channel, New York
5. Sandy Hook Channel, New York
6. New York Harbor
7. Kill Van Kull, New York
8. Thimble Shoals Channel, Virginia
9. Newport News, Virginia
10. Norfolk, Virginia
11. Chickasaw, Alabama
12. Southwest Pass, Mississippi River
13. Lake Charles, Louisiana
14. Galveston Ship Channel, Texas
15. Corpus Christi, Texas
16. New London, Connecticut
17. Puget Sound, Washington
18. Port Arun, Indonesia
19. Coatzacoalcos, Mexico
20. Numerous Open Sea Channel Designs
21. Panama Canal (Under Construction)
22. Tampa Bay, Florida
23. Mississippi River Gulf Outlet (Under Construction)
24. Mobile

Depth/Channel/Banks

- Current, water depth, channel and bank effects (shearing, symmetrical and assymetrical) may be calculated and included in the scenarios and ship model hydrodynamics.

OFF-LINE CAPABILITIES

One-Ship Fast-Time Routine

The main purpose of this program is to verify, without using the on-line simulator components (CGI, wheelhouse, etc.), that the hydrodynamic coefficients of the ship model are operating correctly. It has the capacity to:

- Perform extensive track-plotting
- Simulate effects of bow thruster, shallow water, channels and banks and complex wind for any of the CAORF ship models
- Simulate dolphins and anchors and their respective effects on ship hydrodynamics
- Simulate effects of rudderkick and flanking rudder
- Simulate up to six assist tugs in push, tow and lash modes of operation
- Simulate both a realistic assist tug (hydrodynamics fully developed) or a simplified assist tug (a force in a particular direction).

Two-Ship Fast-Time Routine

This program has all of the features of the above program with the exception of the simulated effects of a realistic (complex) tug. In addition, it can:

- Simulate the passing effects of two ships with both ships having all effects
- Maneuver a waterway or follow a course
- Make available tug assistance; passing ships are provided with an autopilot that can determine: (1) whether tug assistance is required, (2) when the execution of the maneuver to pass begins.

Interactive Steering Validation (Fast-Time)

This program provides the user with:

- A bird's eye view of a particular transit
- An interactive validation run through a transit
- The ability to maneuver the ship (steer and steady-up) from a remote CRT.

DATA ANALYTIC CAPABILITIES

Data collection and analysis is available both automatically (on-line) and through the use of standard computerized packaged programs (off-line).

ON-LINE CAPABILITIES

Approximately 1200 values are automatically recorded from each simulator trial, most consisting of intermediate values for ownship and assist tug hydrodynamic equations. Included in these are the values for immediate use such as:

Ownship: heading, course made good, ground speed, rudder angle, rpm, propeller forces, position, ahead/astern speed, athwartship speed, yaw rate, rate of turn, drift angle, distance of stern and bow from piers, deflection of dolphins (dock pilings/structures).

Assist Tugs: fore and aft and athwartship forces, propeller forces, hydrodynamic forces and the attachment coordinates of tugs.

Target Ships: present speed, present course made good and heading.

Hydrodynamic Equations: ownship forces and moments due to hull, propeller, rudder, banks, current, depth and wind.

On-Line Plotting: Ownship track on a shoreline plot that shows the angle of the rudder on ownship hull outline.

OFF-LINE CAPABILITIES

In house software written specifically to compute:

- Maximum off-track deviation
- Standard deviation of off-track deviations
- Track plotting
- Course changing
- Swept path
- Plot of any recorded parameters

Statistical Package for the Social Sciences (SPSS)

- Descriptive Statistics
- Multiple Analysis of Variance, Covariance
- Multiple Regression (simultaneous, stepwise)
- Multiple Discriminant Analysis
- Factor Analysis, Cluster Analysis
- Non-parametric programs
- Plotting Routines

Biomedical Program D-Series (BMDP)

- Descriptive Statistics
- Analysis of Variance, Covariance, Repeated Measures
- General mixed model of Analysis of Variance
- Stepwise Regression
- Multiple Linear Regression
- Multiple Non-Linear Regression

Physiological Measures

In addition to automatically recorded ship information and standard computer packages, CAORF also has the capability to record human physiological responses such as:

- Electrocardiogram - ECG
- Electromyelogram - EMG
- Electro-occulogram - EOG

STAFF

The CAORF staff reflects an interdisciplinary approach to operations research and is composed of:

Marine Staff

- Deck and engine officers with sea time experience on LNG's, tug and barge units, Great Lakes ore carriers, break bulk freighters, container vessels, SL7's, Lash ships, tankers, U.S. Coast Guard cutters and Navy vessels

Research Psychologists

- Expertise in experimental design
- Perception and cognition background

Hydrodynamicists

Computer Programmers

Engineers

This combination provides a unique blend of experience and knowledge in the design and execution of various research projects.

RESEARCH

Research projects at CAORF may range from port development to bridge risk management to training research studies. Some of the projects currently underway are:

ON-LINE RESEARCH

- Norfolk Harbor Deepening Project
- Panama Canal Widening Project
- Tampa Bay Sunshine Skyway Bridge Assessment
- Cadet Training Research

1. Critical components and effectiveness of components of tasks
2. Transfer of training
3. Development of measures for assessement of training

- Tug Operator Training Research

OFF-LINE RESEARCH

- Generic Port Development Research

- Measures of Workload

- Performance Measures: development of piloted controllability and maneuverability measures

- Interactive Questionnaire: construction of a data base (profile) from information by mariner test subjects.

SPONSORS/CLIENTS

The resources available at CAORF have been utilized by many different agencies, corporations and private companies. Some of the sponsors/clients who have enlisted the aid of CAORF are:

- Defense Mapping Agency (DMA)
- Port of Corpus Christi
- Tennessee Gas Transmission Co. (Teeneco)
- Moore McCormack Bulk Line (Gastrans)
- Northville Industries
- California Coastal Commission
- Mobile - COE
- Norfolk - COE
- Florida - DOT
- Panama Canal Commission
- Sonat Marine, Inc.
- U.S. Navy
- PERTAMINA
- New Orleans Dock Board
- U.S. Coast Guard
- Exxon
- Crowley Maritime Corporation
- U.S. Merchant Marine Academy
- Energy Transport Company
- Port of Galveston

TECHNOLOGY TRANSFER

An important aspect of a research group is to be well knowledged in various areas of research, both specific to its area of research and to other areas of research. CAORF emphasizes the exchange of ideas and research issues through attendance of and presentations at symposia, technological meetings and professional conferences. The following serve as forums for the exchange of research information:

- CAORF Symposium

- International Marine Simulator Forum (IMSF)

- Marine Simulation Conference (MARSIM)

- Society of Naval Architects and Marine Engineers (SNAME)

- American Association of Port Authorities (AAPA)

- Coastal and Ocean Management: Coastal Zone '83

- Dredging Conference Norfolk (sponsored by COE and Old Dominion University)

- Dredging Council Meeting on behalf of the Netherlands

- Conference on Ship Collisions

- Human Factors Society Annual Meeting

- American Psychological Association

In addition to attending and sponsoring conferences, CAORF staff often attend technical demonstrations for new equipment such as RACONS and VIEWNAV (Baltimore 1983).

PRODUCTIVITY AND SAFETY

Over the past eight years not only has CAORF designed and implemented a "man-in-the-loop" approach to keep the U.S. maritime industry competitive, but has also gained information and experience on the design of better ship systems, more effective training techniques and the promotion of safety in all aspects of the marine world.

CAORF OWNSHIP MODELS

SHIP TYPE (DWT)	LENGTH	BEAM	DRAFT
Coal Collier - 150 K Ballasted	915	145	40
Coal Collier - 150 K Loaded	915	145	52
Coal Collier - 225 K Ballasted	1085	178	40
Coal Collier - 225 K Loaded	1085	178	53
Shallow Draft Collier - 150 K Ballasted	940	170	31
Shallow Draft Collier - 150 K Loaded	940	170	45
High Speed Containership - 20 K Loaded	638	100	32.8
Lancer Class Containership - 20 K Loaded	670	85	30.5
Evergreen Class Containership - 18 K Loaded	504	78.7	30.5
Tanker - 30 K Loaded	595	84	34.6
Tanker - 30 K Ballasted	595	84	30.0
Tanker - 65 K Loaded	745	109	40.0
Tanker - 80 K Loaded	763	125	39.9
Tanker - 80 K - 70% Loaded	763	125	32.0
Tanker - 89 K Loaded	774	129	40.0
Tanker - 165 K Loaded	951	155.4	57.0
Tanker - 165 K Ballasted	951	155.4	27.9
Tanker - 250 K Loaded	1085	170	65
Tanker - 250 K Ballasted	1085	170	31.5
LNG - 125 m^3 - G.D. Class	897	143	36.0
LNG - 125 m^3 - N.N. Class	906	135	36.0
Trident Submarine	559	42.0	36.5
Tug - 2200 HP	91.5	27	9.5
Tug/Barge - 50,000 bbl. barge	300	62	15.5
Coast Guard Cutter - (Under Development)			
Panamax Tanker - (Under Development)			
T/V KINGS POINTER			

APPENDIX B

GENERAL DESCRIPTION OF THE REPLACEMENT SUNSHINE SKYWAY BRIDGE AS COMPARED WITH THE EXISTING BRIDGE

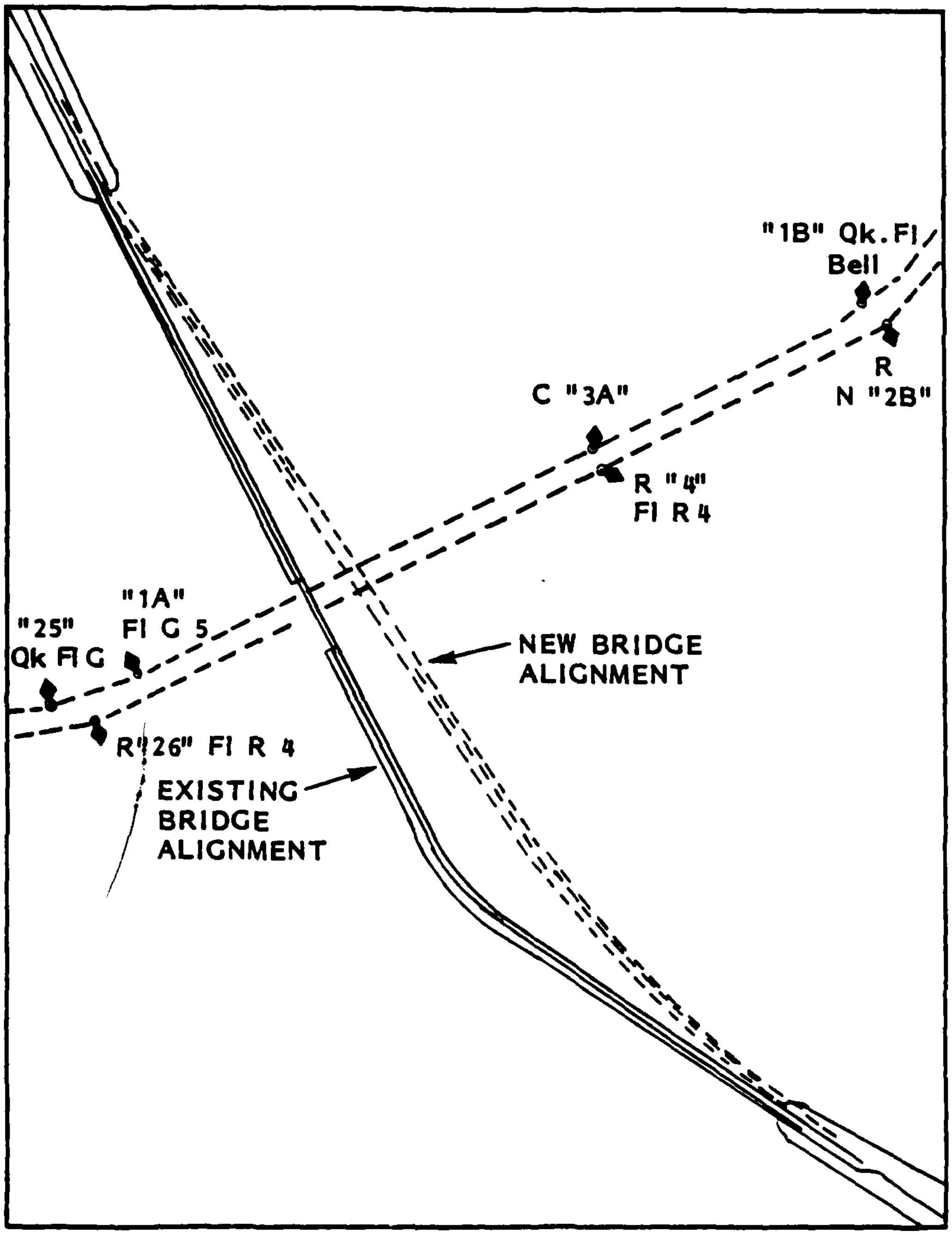


Figure B1. A Comparison of the Alignments of the Existing and New Sunshine Skyway Bridges.

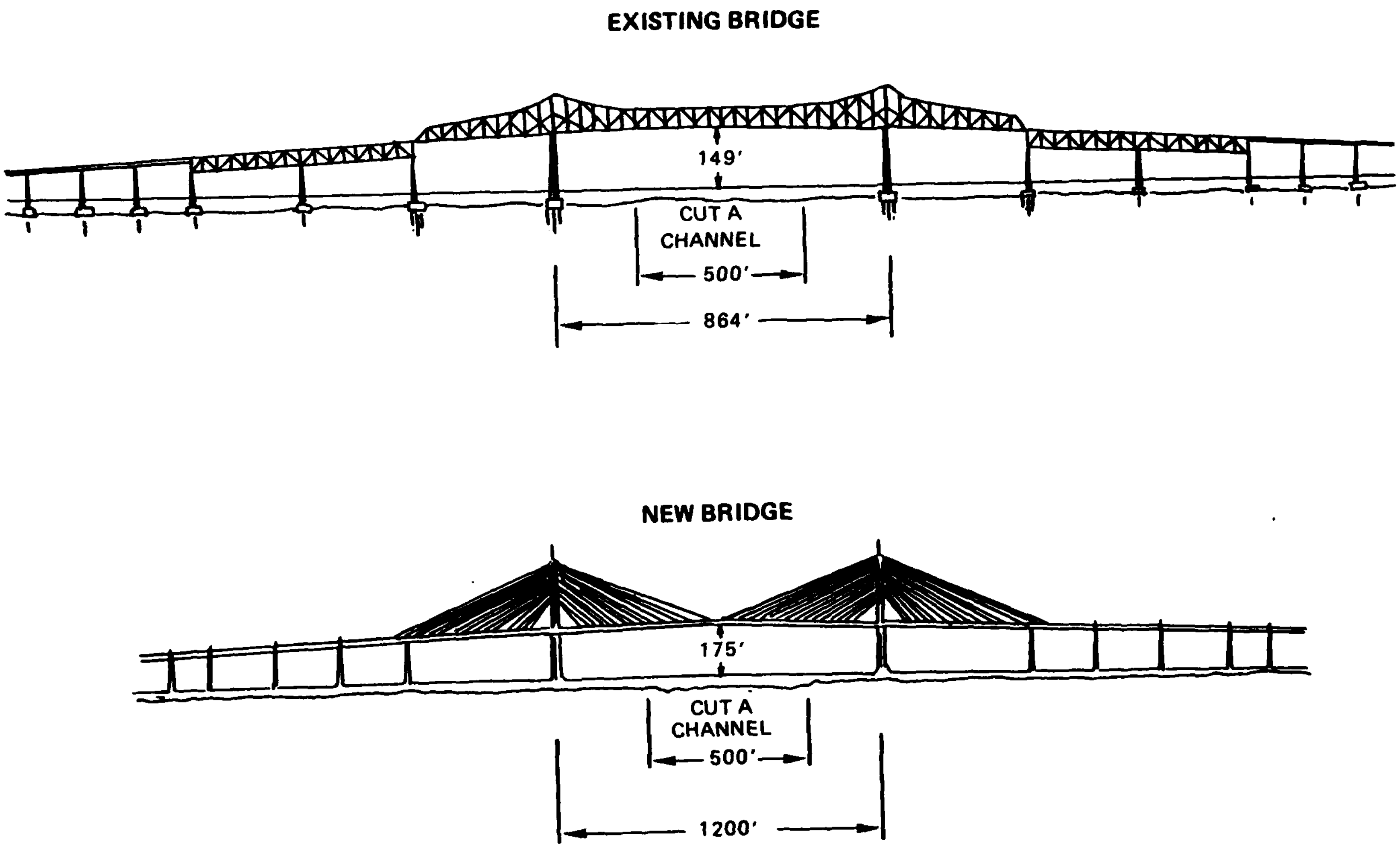


Figure B2. A Comparison of the Designs of the Existing and New Sunshine Skyway Bridges. (Illustrations are not to scale.)

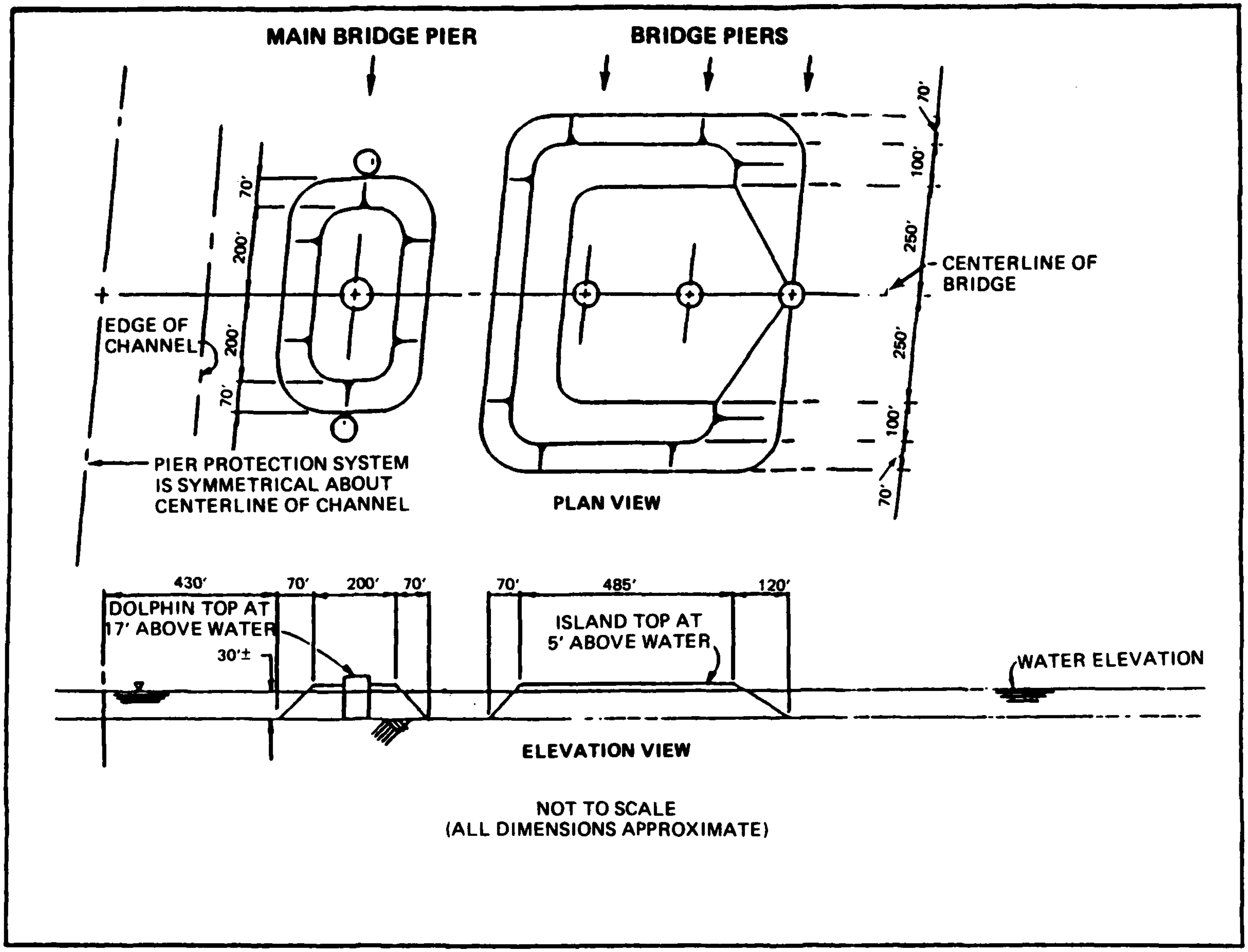


Figure B3. Diagrams of the Pier Protection System for the Replacement Bridge (Top and Side Views), Showing the Positions of the Islands and Dolphins Relative to the Bridge Piers.

APPENDIX C

THE PILOT EVALUATION RATING SCALE AND OPINION QUESTIONNAIRE

PILOTAGE EVALUATION RATING SCALE

Project: ____________________

Pilot No: ____________________

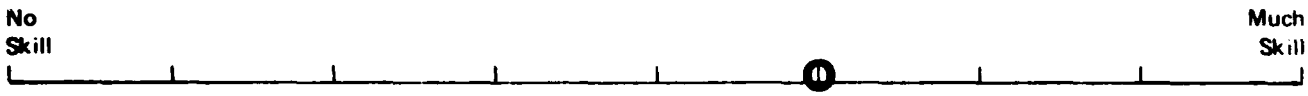
Scenario No: ____________________

Run No: ____________________

Date: ____________________

INSTRUCTIONS

The purpose of these rating scales is to assess various aspects of the trip you just completed. Each scale represents one of the dimensions on which pilotages are to be rated. Please rate the trip by circling the most appropriate point on the scale. For example, the first dimension is "skill required":



SKILL REQUIRED

If making a successful pilotage required a little skill, but less than a moderate amount, then circling the second or third point would probably be appropriate. The third point is circled in the example. If a great deal of skill was required, then circling a point higher up on the scale would be appropriate.

Please rate each dimension in terms of the trip you just completed. Also be sure to rate each and every dimension. If you are not completely sure what to rate for one of them, use your best judgement.

Little Skill							Much Skill

SKILL REQUIRED

Very Simple							Very Complex

TASK COMPLEXITY

Extremely Low							Extremely High

ATTENTION REQUIRED

None							Constant

DEGREE OF MONITORING EQUIPMENT

Easy							Difficult

TASK DIFFICULTY

Easily Controlled							Difficult To Control

VESSEL CONTROLLABILITY

Undemanding							Demanding

TASK DEMANDS

Very Little							Too Much

ENERGY LEVEL REQUIRED

Low							High

STRESS LEVEL

Idle							Very Busy

OVERALL ACTIVITY LEVEL

Refreshed — Exhausted

DEGREE OF RELATED FATIGUE EXPERIENCED AT TERMINATION OF RUN

Little — Much

DEGREE OF EXPERIENCE REQUIRED

Little — Very High

OVERALL WORKLOAD FOR SHIPHANDLER

More Than Enough — Not Enough

TIME TABLE FOR MAKING DECISIONS

Easy — Difficult

EASE OF ACQUIRING INFORMATION

Favorable — Dangerous

SEVERITY OF ENVIRONMENTAL CONDITIONS

Little Need — Great Need

NEED FOR ADDITIONAL BRIDGE PERSONNEL

Very Responsive — Slow To Respond

VESSEL RESPONSIVENESS

Safe — Unsafe

VESSEL SAFETY

TAMPA BAY PROJECT

PILOT OPINION QUESTIONNAIRE

Pilot No.

Date:

This questionnaire is being used to record your opinions concerning the simulation exercises in general and the various conditions you sailed in today. Please feel free to elaborate or explain any of your comments. Additional paper is attached at the end of the questionnaire should you need it. Remember that your answers to these questions will remain completely anonymous. We appreciate your comments and suggestions very much.

1. We are constantly attempting to improve the quality of the simulations we generate. In general, how would you rate the overall realism of the CAORF simulation? In what way was it inadequate?

2. If you were caught in the types of fog and thunderstorm conditions you experienced during the simulation and had to make a bridge passage because it was too late to terminate the trip, how would your real world performance compare with your performance on the simulator? In what ways would it differ? What would have been available in the real world that was not available in the simulation that would have aided making bridge passages?

3. Assuming no equipment failures, did the type of vessel used during the simulation represent a worst case in your opinion? That is, what type of vessel would be worse to pilot than the 165,000 DWT tanker in the types of conditions studied?

4. During the passages you experienced conditions similar to a thunderstorm, that is high winds, limited visibility, and extreme rain clutter on the radar presentation. Did the conditions created during the simulation affect the vessel like you would expect an intense thunderstorm to affect a vessel under such conditions? Was piloting during the simulated "thunderstorm" conditions easier, harder, or the same than it is in the real world? If easier or harder, why?

5. Have you ever had experience with precision navigation aids before? If so, which ones?

6. Did you find piloting with the precision electronic navigation aid simulated at CAORF helpful? If so, in which conditions was it most helpful?

7. Generally speaking, would a device such as this precision navigation instrument be useful as a pilot aid in Tampa Bay? Please explain your answer?

8. What information, in addition to that presented in the CAORF precision navigation aid, would you like to see presented by such an instrument?

9. Did you prefer the graphic display, the digital display, or some combination of both?

10. With respect to making a safe bridge passage, did you feel there was much difference between the turn from Mullet Key into Cut A Channel as it exists now and the turn as it was modelled in the extended Cut A Channel?

11. From a pilot's perspective, would you like to see the extended Cut A Channel design implemented in Tampa Bay?

12. Would you have any confidence in the results from this study with regard to the usefulness of precision electronic navigation aids or the evaluation of channel designs for piloting under adverse environmental conditions? Please explain your answer.

13. We would like to have any other comments you may have regarding any aspect of this study or CAORF in general. Please feel free to be candid as your comments may help us do a better job in the future.

Thank you very much for your time and effort in answering these questions and in participating in the study as a whole. Your help with this project is greatly appreciated. We hope you have enjoyed your stay here and found your experience at CAORF worthwhile.

APPENDIX D

SCENARIO DESCRIPTIONS

SCENARIO A

CONDITION – Familiarization Exercise

TAMPA BAY MODEL – Existing Channel/New Bridge

PENA* – Yes

CURRENT – 2 knots flood

WIND – 8 knots from 285°T±45°

VISIBILITY – Clear, 8 nm, daylight

INITIALIZATION POINT – Abeam of buoy "23" in center of Mullet Key Channel

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO B

CONDITION – Familiarization Exercise

TAMPA BAY MODEL- Extended Cut A Channel/New Bridge

PENA* – Yes

CURRENT – 2 knots flood

WIND** – 8 knots from 285°T±45°

VISIBILITY** – Clear, 8 nm, daylight

INITIALIZATION POINT – Center of Egmont Channel, midway between buoys "19" and "21"

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 100°T

INITIALIZATION HEADING – 100°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO 1

CONDITION – Experimental Condition 1

TAMPA BAY MODEL – Old Channel(Old Bridge)

PENA* – *No*

CURRENT – Slack

WIND – 8 knots from 285°T±45°

VISIBILITY – Clear, 8 nm, daylight

INITIALIZATION POINT – Abeam of buoy "C15" in center of Mullet Key Channel

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

*Precision Electronic Navigation Aid

**Introduce fog and thunderstorm conditions after turn into Cut A Channel at experimenter's request

SCENARIO 2

CONDITION – Experimental Condition 2

TAMPA BAY CHANNEL – Old Channel/Old Bridge

PENA* – No

CURRENT – 2 knots flood

WIND – Initialize at 8 knots from 285°T±45°. At .5 nm west of buoy "R2A" change to 40 knots with gusts ± 10 knots from 330°T±45°.

VISIBILITY – Initialize at clear, 8 nm, daylight. At .5 nm west of buoy "R2A" change:

- Visibility to .10 nm
- RSG control to 10 (sever rain clutter on radar)
- Sun dial/ambient to dusk condition

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO 3

CONDITION – Experimental Condition 3

TAMPA BAY MODEL – Old Channel/Old Bridge

PENA* – No

CURRENT – 2 knots flood

WIND – 8 knots from 285°T±45°

VISIBILITY – Fog, .1 nm, daylight

INITIALIZATION POINT – Abeam of buoy "C15" in center of Mullet Key Channel

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO 4

CONDITION – Experimental Condition 4

TAMPA BAY MODEL – Existing Channel/New Bridge

PENA* – No

CURRENT – 2 knots flood

WIND – Initialize at 8 knots from 285°T±45°. At .5 nm west of buoy "R2A" change to 40 knots with gusts ± 10 knots from 330°T±45°.

VISIBILITY – Initialize at clear, 8 nm, daylight. At .5 nm west of buoy "R2A" change:

- Sun dial/ambient to dusk condition
- Visibility to .10 nm
- RSG control to 10 (severe rain clutter on radar)

INITIALIZATION POINT – Abeam of buoy "23" in center of Mullet Key Channel

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

*Precision Electronic Navigation Aid

SCENARIO 5

CONDITION – Experimental Condition 5

TAMPA BAY MODEL – Existing Channel/New Bridge

PENA* – No

CURRENT – 2 knots flood

WIND – 8 knots from 285°T±45°

VISIBILITY – Fog, .1 nm daylight

INITIALIZATION POINT – Abeam of buoy "23" in center of Mullet Key Channel

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO 6

CONDITION – Experimental Condition 6

TAMPA BAY MODEL – Existing Channel/New Bridge

PENA* – Yes

CURRENT – 2 knots flood

WIND – Initialize at 8 knots from 285°T±45°. At .5 nm west of buoy "R2A" change to 40 knots with gusts ± 10 knots from 330°T±45°.

VISIBILITY – Initialize at clear, 8 nm, daylight. At .5 nm west of buoy "R2A" change:

- Sun dial/ambient to dusk condition
- Visibility to .10 nm
- RSG control to 10 (severe rain clutter on radar)

INITIALIZATION POINT – Abeam of buoy "23" in center of Mullet Key Channel

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO 7

CONDITION – Experimental Condition 7

TAMPA BAY MODEL – Existing Channel/New Bridge

PENA* – Yes

CURRENT – 2 knots flood

WIND – 8 knots from 285°T±45°

VISIBILITY – Fog, .1 nm, daylight

INITIALIZATION POINT – Abeam of buoy "23" in center of Mullet Key Channel

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 081°T

INITIALIZATION HEADING – 081°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO 8

CONDITION – Experimental Condition 8

TAMPA BAY MODEL – Extended Cut A Channel/New Bridge

*Precision Electronic Navigation Aid

PENA* – No

CURRENT – 2 knots flood

WIND – Initialize at 8 knots from 285°T±45°. At .5 nm southwest of buoy "R2A" change to 40 knots with gusts ± 10 knots from 330°T±45°.

VISIBILITY – Initialize at clear, 8 nm. At .5 nm west of buoy "R2A" change:

- Sun dial/ambient to dusk condition
- Visibility to .10 nm
- RSG control to 10 (severe rain clutter on radar)

INITIALIZATION POINT – Center of Egmont Channel midway between buoys "19" and "21"

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 100°T

INITIALIZATION HEADING – 100°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

SCENARIO 9

CONDITION – Experimental Condition 9

TAMPA BAY MODEL – Extended Cut A Channel/New Bridge

PENA* – No

CURRENT – 2 knots flood

WIND – 8 knots from 285°T±45°

VISIBILITY – Fog, .1 nm, daylight

INITIALIZATION POINT – Center of Egmont Channel midway between buoys "19" and "21"

INITIALIZATION SPEED – 10 knots

INITIALIZATION COURSE – 100°T

INITIALIZATION HEADING – 100°T

INITIALIZATION RUDDER ANGLE – 0°

TERMINATION POINT – When stern clears all bridge structures in Cut A Channel

*Precision Electronic Navigation Aid

APPENDIX E

PILOT BRIEFING INFORMATION

INFORMATION TO PILOTS

The staff at the National Maritime Research Center's Computer Aided Operations Research Facility (CAORF) would like to welcome you to the simulator and thank you for your participation in this study. From the start we would like to make it clear that everything that transpires on the CAORF bridge will be kept completely confidential. In addition, we would like to make it clear that we will not rate or pass judgement on your professional skills or competency as a pilot during the course of this research or during subsequent analysis of data. In fact, the case is quite the contrary! We are seeking your expertise and assistance in the evaluation of several proposals to make vessel passage under the Sunshine Skyway Bridge safer. Thus we are using your skill as a pilot as a basis for making our evaluations.

During the course of your participation in this experiment you will be asked to make several passages through the Sunshine Skyway Bridge area of Tampa Bay. Several different approaches will be examined:

1. Using the basic channel configuration that exists in Tampa Bay now and the old (current but full twin span) Sunshine Skyway Bridge.

2. Using the basic channel configuration that exists in Tampa Bay now and the New Sunshine Skyway Bridge which is currently under construction.

3. Using a new channel configuration and the new Sunshine Skyway Bridge. The new channel configuration represents an extension of Cut A Channel approximately two miles seaward. This extended Cut A Channel intersects with an extension of Egmont Channel. Mullet Key Channel is, therefore, eliminated.

Charts are available on the Chart Table for each of these approaches. In combination with these different approaches some passages will be made with the aid of a precision positioning navigation aid. We call the CAORF system "PENA" (Precision Electronic Navigation Aid). It is similar to other precision positioning systems currently in use and presents both graphic and digital displays of vessel position information. The use of this system will be demonstrated during a familiarization exercise designed to acquaint you with the simulator. The PENA system will be available during only two of your passages; others will be made without it.

In addition to the different approaches and equipment, passages will differ in terms of the environmental conditions under investigation. You will be asked to make passages under favorable conditions, heavy fog conditions, and intense thunderstorm conditions. We fully realize that you might not actually proceed with a passage under some of these conditions in the real world. We ask that you please make the best possible passage in all conditions for the purposes of this study. At the point where in real life you would anchor or take other action to terminate the passage please note that fact to the mate on the bridge, but continue the passage. Again we would like to emphasize that we are evaluating the degree of safey associated with different bridge approaches with different equipment made available to pilots. As such we ask that you not anchor your vessel. Proceed with each bridge passage "as if" you could not abort or terminate the passage for any reason.

The specific conditions in effect for each of your passages will be explained to you prior to each passage.

The vessel being used in this study is a light 165,000 DWT tanker. Attached you will find a sheet containing the dimensions and maneuvering characteristics of the vessel. Also attached is a sheet lising the equipment contained on the CAORF bridge. During the familiarization exercise one of our staff will show you all equipment.

Your crew for all passages will consist of a helmsman whose services you should use as you would normally when piloting a ship. A mate will also be present on the bridge and again you can use the mate as you would normally. In addition, you have a lookout positioned on the bow. You can communicate with the lookout using the sound powered phone. The lookout will respond to your questions as accurately as possible given the immediate environmental conditions.

Following each passage you will be asked to complete a brief questionnaire evaluating the trip you just made. In addition, when you complete all your passages, we will ask you for your opinions on various aspects of the study.

We would like to take this opportunity to again thank you for your participation in the research effort and we hope your stay here is a pleasant one. If you have any questions, please feel free to ask.

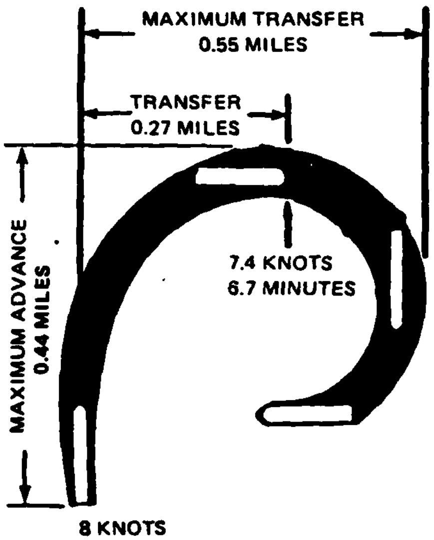
OWNSHIP BRIDGE EQUIPMENT

- Steering stand with gyro repeater, rate of turn indicator
- Overhead 3-face rudder angle indicator
- Bulkhead mounted gyro repeater
- Rate of turn indicator
- Engine order repeater
- RPM indicator (2)
- Engine order telegraph/throttle
- Speed log (through the water speed)
- Digital distance log
- Digital clock
- VHF radio-telephone
- Manual whistle control
- Automatic whistle timer control
- Sound powered phone
- Digital depth sounder
- Relative wind indicators (speed and direction)
- Bridge wing gyro repeater with pelorus mounted (2)
- 3 cm and 10 cm radars (with computerized plotting aid)
- Precision Electronic Navigation Aid (PENA) (available for certain passages only)

DEEP WATER MANEUVERING CHARACTERISTICS AND DESCRIPTION INFORMATION

TURNING CIRCLE DIAGRAM

BALLASTED LOAD/HALF SPEED



FINAL DIAMETER 0.43 MILES

DRAFT FWD 24'   DRAFT AFT 31'

Length	951'
Beam	155.4'
Draft	27.9'
Capacity	165,000 DWT

Maximum Rudder Angle	STARBOARD RIGHT 40°	PORT LEFT 40°

TIME AND DISTANCE CRASH STOP

Engine Order	Full Lead	
	Time (Min.)	Distance Miles
Full Sea Speed	11.7	1.22
Full Ahead	5.6	0.61
Half Ahead	5.0	0.35
Slow Ahead	3.9	0.11

ENGINE ORDER/R.P.M./SPEED

Engine Order	RPM	Speed (Knots) Full Load
Full Sea Speed	95	17.4
Full Ahead	60	9.3
Half Ahead	40	5.6
Slow Ahead	20	4.2
Dead Slow Ahead	10	1.1
Dead Slow Astern	10	
Slow Astern	20	
Half Astern	33	
Full Astern	50	Time Full Ahead RPM to Full Astern 67 Seconds

Warning:

The response of the ship may be different from that listed if any of the following conditions, upon which the maneuvering information is based, are varied:

1. Calm weather—10 knots or less, calm sea.
2. No current
3. Water depth 3 times the ship's draft or greater.
4. Clean hull.
5. Intermediate drafts or unusual trim.

Notes:

1. Data is for steady speeds only. A kick turn maneuver trajectory, for example, will provide less advance.
2. There is no appreciable difference in the time or distance of ADVANCE or TRANSFER when making a turn to port or starbord. Therefore, while the diagram shows a starboard turn, symmetrical information would apply when turning to port.
3. Advance, Transfer, and Diameter are about the same regardless of initial speed. At initial speeds slower than Half Ahead, the speed at any point in the maneuver will be less than shown on the half speed diagram, and times to maneuver will be greater than shown.
4. Maximum available rudder angle and constant engine order are maintained.
5. Final diameter is measured across outer boundary of the swept path.
6. In actual operation, the ship does not stop along a straight path. Therefore, head reach will actually be less than shown and there may be appreciable side reach.

APPENDIX F

ANALYSIS OF VARIANCE SUMMARY TABLES: EFFECT OF THE ENVIRONMENT ON PROXIMITY AND CONTROLLABILITY VARIABLES

TABLE F1. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = CLOSEST POINT OF APPROACH TO BRIDGE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	29231.73	3.00	< 0.10
Nav. Sys. Des. (N)	3	52283.39	5.37	< 0.005
NE	3	991.06	< 1	–
Error	42	9738.67		

TABLE F2. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE DISTANCE FROM BRIDGE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	29235.98	2.68	–
Nav. Sys. Des. (N)	3	40422.02	3.70	< 0.025
NE	3	3893.92	< 1	–
Error	42	10918.61		

TABLE F3. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY IN DISTANCE FROM BRIDGE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	2262.08	16.38	< 0.0005
Nav. Sys. Des. (N)	3	108.68	< 1	–
NE	3	220.04	1.59	–
Error	42	138.08		

TABLE F4. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE YAW RATE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	0.046	2.21	–
Nav. Sys. Des. (N)	3	0.091	4.37	< 0.01
NE	3	0.012	< 1	–
Error	42	0.021		

TABLE F5. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF YAW RATE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	< 0.001	< 1	–
Nav. Sys. Des. (N)	3	< 0.001	< 1	–
NE	3	0.003	< 1	–
Error	42	0.003		

TABLE F6. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF HEADING

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	6.40	2.02	–
Nav. Sys. Des. (N)	3	26.00	8.19	< 0.0005
NE	3	1.99	< 1	–
Error	42	3.18		

TABLE F7. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE SWEPT PATH

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	35298.39	16.33	< 0.0005
Nav. Sys. Des. (N)	3	10107.23	4.68	< 0.01
NE	3	909.53	< 1	–
Error	42	2161.39		

TABLE F8. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF SWEPT PATH

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	2367.46	9.42	< 0.005
Nav. Sys. Des. (N)	3	2783.88	11.08	< 0.0005
NE	3	126.49	< 1	–
Error	42	251.21		

TABLE F9. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE RUDDER ANGLE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	39.88	1.79	–
Nav. Sys. Des. (N)	3	39.43	1.77	–
NE	3	10.02	< 1	–
Error	42	22.26		

TABLE F10. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF RUDDER ANGLE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	13.68	2.40	–
Nav. Sys. Des. (N)	3	27.44	4.81	< 0.01
NE	3	4.39	< 1	–
Error	42	5.70		

TABLE F11. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = NUMBER OF RUDDER REVERSALS

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	.875	< 1	–
Nav. Sys. Des. (N)	3	2.73	1.03	–
NE	3	3.69	1.39	–
Error	42	2.64		

TABLE F12. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE DEVIATION FROM CENTERLINE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	8224.39	< 1	–
Nav. Sys. Des. (N)	3	13195.39	1.27	–
NE	3	4175.11	< 1	–
Error	42	10427.79		

TABLE F13. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF DEVIATION FROM CENTERLINE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	476.21	< 1	–
Nav. Sys. Des. (N)	3	5453.23	5.52	< 0.005
NE	3	754.57	< 1	–
Error	42	988.69		

APPENDIX G

ANALYSIS OF VARIANCE SUMMARY TABLES:

EFFECTS OF NAVIGATIONAL SYSTEM DESIGNS

ON PROXIMITY VARIABLES

TABLE G1. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = CLOSEST POINT OF APPROACH TO BRIDGE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	20395.95	4.28	< 0.01
Error	24	4765.36		

TABLE G2. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE DISTANCE FROM BRIDGE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	17538.88	3.12	< 0.05
Error	24	5615.32		

TABLE G3. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY IN DISTANCE FROM BRIDGE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	107.72	1.47	–
Error	24	73.36		

APPENDIX H

ANALYSIS OF VARIANCE SUMMARY TABLES: EFFECTS OF NAVIGATIONAL SYSTEM DESIGN ON CONTROLLABILITY VARIABLES

TABLE H1. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE YAW RATE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	0.038	2.58	< 0.10
Error	24	0.015		

TABLE H2. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF YAW RATE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	< 0.001	< 1	–
Error	24	0.002		

TABLE H3. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF HEADING

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	10.41	6.40	< 0.001
Error	24	1.63		

TABLE H4. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE SWEPT PATH

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	3963.04	4.88	< 0.01
Error	24	812.19		

TABLE H5. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF SWEPT PATH

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	1046.18	9.74	< 0.0005
Error	24	107.37		

TABLE H6. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE RUDDER ANGLE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	14.79	1.36	–
Error	24	10.87		

TABLE H7. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF RUDDER ANGLE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	10.31	4.32	< 0.01
Error	24	2.39		

TABLE H8. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = NUMBER OF RUDDER REVERSALS

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	2.80	1.38	–
Error	24	2.03		

TABLE H9. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = AVERAGE DEVIATION FROM CENTERLINE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	7390.34	1.23	–
Error	24	6009.26		

TABLE H10. EFFECTS OF NAVIGATIONAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = VARIABILITY OF DEVIATION FROM CENTERLINE

Source	Degrees of Freedom	Mean Square	F	Prob.
Navigation Condition	4	2065.92	3.13	< 0.05
Error	24	659.52		

APPENDIX I

ANALYSIS OF VARIANCE SUMMARY TABLES:

EFFECTS OF NAVIGATIONAL SYSTEM DESIGNS AND

ENVIRONMENTAL CONDITIONS ON PILOT SCENARIO EVALUATIONS

TABLE I1. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = COGNITIVE LOAD

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	340.07	20.24	< 0.0005
Nav. Sys. Des. (N)	3	16.64	< 1	–
NE	3	4.64	< 1	–
Error	42	16.80		

TABLE I2. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = STRESS LEVEL

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	248.64	23.98	< 0.0005
Nav. Sys. Des. (N)	3	3.62	< 1	–
NE	3	4.07	< 1	–
Error	42	10.37		

TABLE I3. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = TASK DIFFICULTY

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	418.02	30.34	< 0.0005
Nav. Sys. Des. (N)	3	3.45	< 1	–
NE	3	14.35	1.04	–
Error	42	13.78		

TABLE 14. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = SHIPHANDLING DIFFICULTY

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	3.02	< 1	–
Nav. Sys. Des. (N)	3	15.07	3.57	< 0.05
NE	3	2.97	< 1	–
Error	42	4.22		

TABLE 15. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = OPERATOR WORKLOAD EVALUATION

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	6.45	4.45	–
Nav. Sys. Des. (N)	3	0.30	< 1	–
NE	3	0.49	< 1	–
Error	42	1.45		

TABLE 16. EFFECTS OF ENVIRONMENTAL CONDITION ANALYSIS OF VARIANCE SUMMARY TABLE

DV = TOTAL WORKLOAD SCORE

Source	Degrees of Freedom	Mean Square	F	Prob.
Env. Cond. (E)	1	3861.16	25.73	0.0005
Nav. Sys. Des. (N)	3	110.11	< 1	–
NE	3	46.02	< 1	–
Error	42	150.08		

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